# DARES Focus Area #2:

## Abiotic Organic Production & Evolution within Planetary Environments

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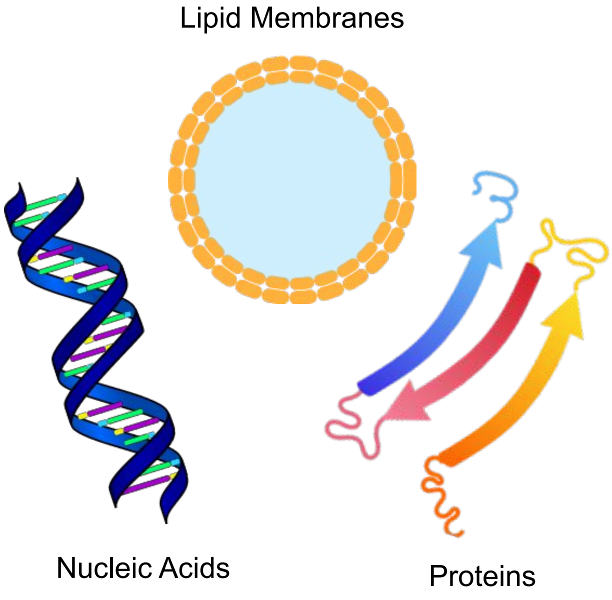
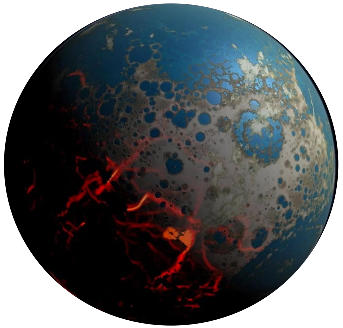
**Secondaries:** Laurie Barge & Tanja Bosak

Image Credit: NASA

# Overview

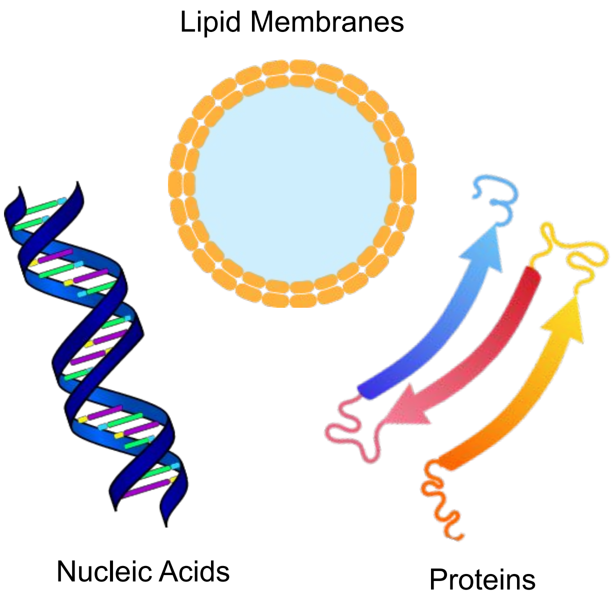
**IN THE PREVIOUS DECADE** much work focused on the origin of **biological building blocks** (BBs) in environments relevant to **early Earth** and to a lesser extent astrophysical environments, Mars, and ocean worlds. However, this approach inherently **limits our understanding of potential bottlenecks** in chemical evolution and the possibility for life as we both do and don't know it to emerge on other planetary bodies.



Early Earth
Credit: Simone Marchi/NASA

# Overview

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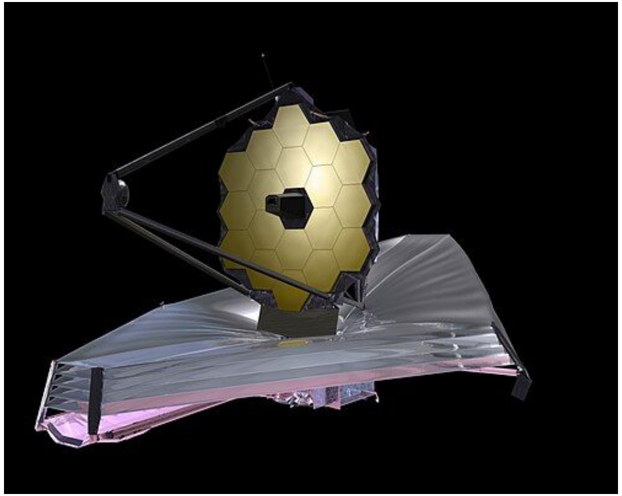
Credit: NASA


Credit: Lick Observatory

**MOVING FORWARD**, this topic highlights the need to expand our understanding of abiotic chemistry beyond prebiotic chemistry relevant to Earth, including the chemical evolution of **non-biologically relevant** organic molecules. This would also support studies investigating abiotic synthesis on **planetary bodies that may not be habitable for life** or life as we know it.

# Importance to NASA Astrobiology

- **Abiotic** chemical evolution vs **Prebiotic** chemistry
- What conditions are conducive for life to emerge?
- **Abiotic** chemistry on **other worlds benchmarks** lab work & computer simulations
- **Probability** of finding **Earth-like** life and **exotic life**
- **Agnostic biosignatures** is a growing field of study
  - e.g. Grefenstette et al 2024, Astrobiology Primer Ch 9, *Astrobiology*, vol 24
- Recognition of **inherent risk** of missions only highlighting life detection
  - e.g. Davila & Eigenbrode 2024, *JGR*, vol 129
- Relevant to **astromaterial** studies, sample **return**, **life detection**, **human** exploration, **exoplanets**



JWST - Credit: NASA

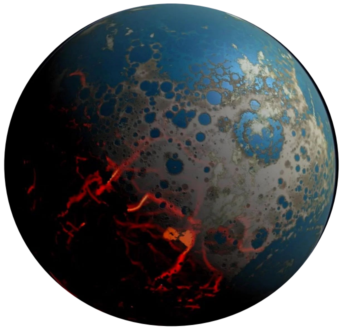
# Importance to NASA Astrobiology

- Importance highlighted in foundational documents:
  - 2015 NASA Astrobiology Strategy
  - NASEM OWL Decadal Survey
    - Molecule evolution and delivery (Q1, 3, 4, 10); OoL on Earth (Q9); life detection (Q11); Life detection on exoplanets (Q12)
  - Standards for Evidence of Life Workshop Report
  - PCE3-NOW-NFoLD - Abiotic Baseline Report
  - NASEM Astrobiology for Human Exploration of Mars
  - Relevant to AGs: LEAG, VEXAG, SBAG, EXMAG, OPAG, MEPAG, ExoPAG
  - 2018 NASEM Exoplanet Science Strategy
    - Calls for evaluating potentially habitable worlds & searching for life
    - OoL needed for life

## F1: Much progress has been made in prebiotic chemistry relevant to early Earth (i.e. Earth centric)

- In the past decade we've learned biological building blocks:
  - form under a wide-range of environments (aqueous chemistry under conditions relevant to Earth)
    - Reactions can be driven by minerals, inorganic reactants, or organic catalysts
    - Isotopes can elucidate mechanisms
  - Can form in astrophysical environments
  - Could have been delivered to early Earth via meteorites

- Planetary exploration also supports this assertion
  - Long chain alkanes and aromatics on Mars (SAM-MSL)
  - Mars meteorites: amino acids
  - Organics are widespread (but are the BBs?)



Early Earth
Credit: Simone Marchi/NASA

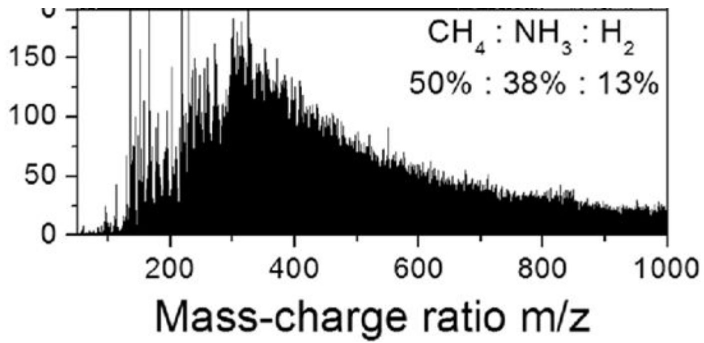
## **F2:** Studies of abiotic synthesis under conditions beyond what is relevant to Earth and what is considered habitable for Earth-like life can reveal bottlenecks in abiotic chemical evolution

- Abiotic chemistry on worlds that may not support life as we know it
  a. Provide opportunities to benchmark lab studies
  b. May represent environmental endmembers, helping map phase space
  c. Examples
     - Sulfuric acid clouds on Venus
     - Methane/ethane lakes on Titan
     - Surface ices of the Moon
     - Ceres - a relict ocean world
  d. Can reveal importance of environmental variables (e.g. at what pH is organic synthesis untenable?)

# F3: The chemical evolution of non-biological compounds can inform selective pressures for biomolecules as well as what biochemistries may be possible for life as we don't know it

- Abiotic chemistry generates a wide swath of organic compounds, most of which are not biologically relevant to life on Earth
  a. With a focus on BBs, much of these organic compounds are ignored.
  b. We thus lack a holistic understanding of the chemical evolution of organic matter

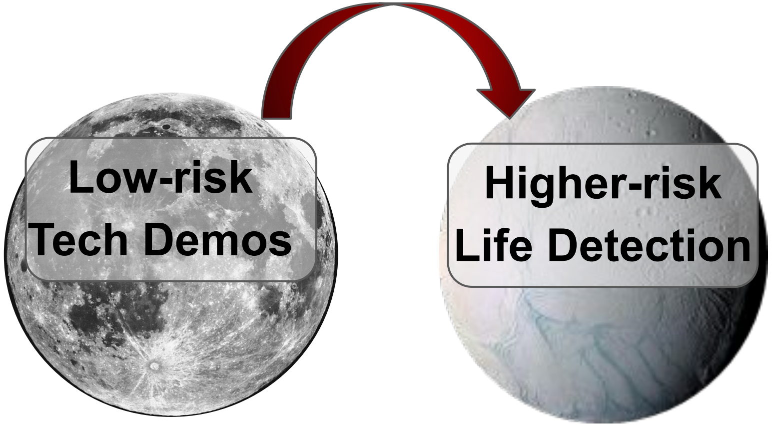
- Reveals:
  a. Selection pressures for molecular sets (e.g. stability, functionality)
  b. Possibility for alien biochemistries (e.g. proteins made of beta AAs)
  c. Conditions that could favor life as we know it vs don't know it




BBs have been identified in abiotic reactions, but they are just a few of many compounds generated. Right - mass spectrum of Miller-Urey reaction. Ref: Wollrab et al. Orig Life Evol Biosph. 2016.

## F4: Planetary bodies uninhabitable for life as we know it can provide unique opportunities for field testing (relates to DARES Focus Area #6)

- Moon, Venus, Ceres(?)
- Test life detection suites with abiotic samples
  a. lowers risk for subsequent missions to OWs
  b. Identify sources of contamination w/rovers and/or astronauts
  c. Requires characterizing abiotic chemistry of these worlds



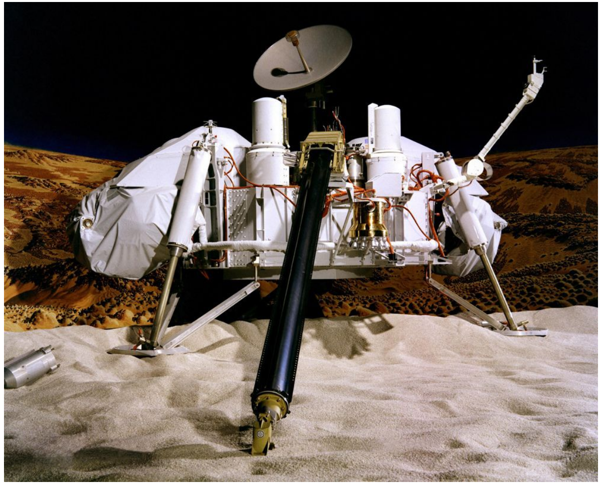

Credit: Lick Observatory          Credit: NASA JPL/Caltech

## F5: Studies of abiotic chemical evolution in different environments are critical for describing the abiotic baseline and facilitating life detection efforts

- Abiotic baseline varies with the environment being studied
    a. Must know what is abiotically feasible / preservable
    b. Needed to differentiate false vs true biosignature detection
    c. Called out by Standards of Evidence & Abiotic Background Workshop Reports
    d. Non-biological abiotic compounds could mimic the observables characteristic of biosignatures

# F6: Planetary missions should highlight the importance of characterizing abiotic organic compounds not just for life detection, but also to improve our understanding of conditions conducive for the OoL

- Need to improve relevance of abiotic chemistry for OoL in mission STMs / objectives (outside of life detection & habitability assessment)
- Contribute to arguments for including astrobiology in Moon exploration
- Reduce risk for life detection missions - no life is NOT a failure!



Viking Mars Lander. Credit: NASA

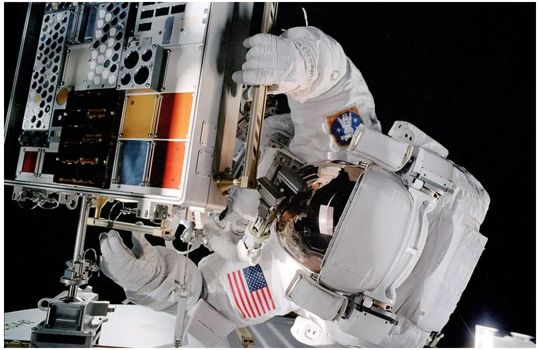
# F7: Exclusions in ROSES discouraged proposals of abiotic studies unrelated to OoL & habitable worlds.

- Context: 2015 Astrobiology Strategy did not emphasize abiotic chemistry on worlds where life may not have emerged / emerged with novel biochemistries

- Exobiology
  a. "study of the formation of abiotic organic molecules where the research is not specifically focused on the origin of life" is excluded
- Emerging Worlds
  a. Studies of abiotic organic molecules are "generally within the scope of Emerging Worlds, but only if the proposal makes an explicit, clear, and cogent case that the specific research advances the understanding of the origin or early evolution of the Solar System
- Habitable Worlds
  a. "Models of environments in which organic chemical synthesis could occur and the forms in which prebiotic organic matter has been preserved in planetary materials should be directed to C.5 Exobiology"
- Solar System Working
  a. "Studies of the formation of prebiotic organic molecules where the research is specifically focused on the origin of life are not within scope of this program element, but may be within scope of Exobiology"

# F8: Abiotic chemical evolution should support:

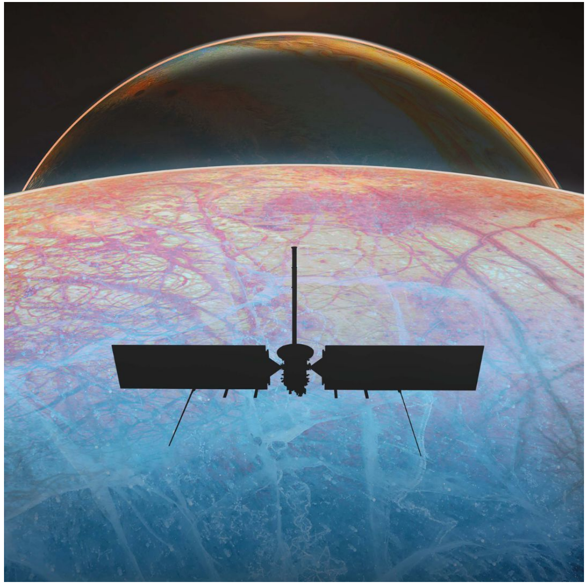
- Laboratory studies - including potentially long-term studies (>3 yrs)
- Computational simulations / models / ML
- Studies of ancient Earth rocks / Earth meteorites
- Astromaterials on Earth
- Planetary missions
- Astronaut Experiments
- Telescopic Observations



Astronauts can enable unique condition testing for abiotic chemistry. Credit: NASA

# Why this Focus Area Now?

- Abiotic sources for the BBs have been demonstrated in diverse Earth-relevant environments
- Not as well studied - other molecules
- Improved instrumentation & AI
  - We can start to tackle abiotic chemistry of non-biological molecules
  - Can better characterize organics on other worlds in situ
- Growing interest in life detection missions
  - Mars Sample Return, Mars Life Explorer
  - Ocean worlds (Europa Lander, Enceladus Orbilander)
- Human space exploration
  - Moon-to-Mars program will forever change pristine landscapes
  - Need to leverage first missions to characterize contamination
  - Can be leveraged to obtain unprecedented sample sizes / diversity
- Age of Venus & Titan exploration
  - Can they support life?
  - Important analog for exoplanets
- Sample return missions/mission concepts are gaining traction
  - Comet, Ceres, Mars, MMX, Artemis
- JWST & HWO planning
  - Age of exoplanet discovery



Europa Clipper is equipped with a high resolution mass spectrometer. Credit: NASA-JPL/Caltech

# Why this Focus Area Now?

## 2015 NASA Astrobiology Strategy:

1. **THEN:** Topic 1 - Identifying abiotic sources of organic compounds focused on helping understand the origin of BBs to establish the inventory of organics for the OoL on Earth.
2. **THEN:** abiotic chemistry in Earth-like conditions (early Earth or elsewhere) or small bodies that could could deliver / promote formation of Earth-like life
3. **THEN:** mentioned alternative biochemistries, but not emphasized.
4. **THEN:** elucidate conditions for habitability

## Adding to 2015 Strategy, DARES:

1. **NOW:** this topic is not constrained to abiotic sources for the BBs of Earth-like life, but includes studies of non-biological molecules
2. **NOW:** study abiotic chemistry outside conditions relevant to Earth or worlds habitable for Earth-like life. Expand to exoplanets with diverse conditions.
3. **NOW:** investigate chemical evolution & functionality of non-biological molecules
4. **NOW:** expand to conditions for OoL
5. **NOW:** leverage human space exploration to expand abiotic studies
6. **NOW:** leverage uninhabitable worlds to investigate abiotic baselines & tech demos

# Focus Area Landscape

## Topic 1: Protometabolism & Synthesis / Function of Macromolecules

- Protometabolism studies
- Co-evolution of bio-polymers
- Cell encapsulation of bio-polymers

-Relevance directly ties to OoL for life as we know it

**Goal: under what conditions do the BBs evolve to form Earth-like life?**

BB chemistry on Earth & habitable worlds

Abiotic baseline of habitable worlds

## Topic 2: Abiotic Organic Production & Evolution

- Chemical evolution of non-biological building blocks

-Abiotic chemistry on worlds not habitable for life or life as we know it

-Relevance does not have to directly tie into prebiotic chemistry / OoL

-Field Testing Instrumentation / Contamination / PP protocols

**Goal: understand phase space of abiotic chemistry & chemical evolution**

# Additional Discussion Points

1. Should this topic include evolution of Si-based life?
2. Should there be a discussion on inorganic chemical evolution?
3. How can we improve incorporation of abiotic chemistry / OoL objectives for missions *outside* of life detection? Can we establish benchmarks for chemical evolution?
4. Future of astrobiology: how does emergence of life or abiotic chemistry over time influence likelihood for life to emerge? Where does this fit?

# Summary Slide

1. Charting **abiotic chemistry**—even in **uninhabitable settings** and with **non-biological molecules**—would reveal conditions conducive for the emergence of life (Earth-like or not) and facilitate life detection efforts

2. Studying abiotic chemistry on the Moon, Venus, and Ceres or using experimental samples can reduce the risk of life detection missions to other worlds

3. Astrobiology should be incorporated into human exploration objectives early

4. Abiotic chemistry is important outside of life detection