The Search for Life in the Universe
Jim Cordes, Shami Chatterjee

Recently: Life, its origin, early Earth, Mars.
Today: Habitable moons?

Reading: As posted.
Term paper or debate topics? Please confirm if not already done.

Empirical Estimates of Habitable Zones

• Stellar luminosity: more massive stars are hotter and bigger.
• So, Earth-equivalent radiation further away from star:
  \[
  \frac{L_\star}{D_{\text{equiv}}^2} = \frac{L_{\text{Sun}}}{D_{\text{Earth}}^2}
  \]

• HZ limits depend on many factors!
  – Atmospheric composition and greenhouse effect.
  – Clouds and reflection of incoming radiation.
  – Feedback like the Carbonate-Silicate cycle.

• Very crudely, 170% to 25% of current solar flux at 1AU?
  \( \Rightarrow \) So ~0.75 AU to 2 AU for G-type star.
ALH84001: Evidence for Life on Mars?
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McKay et al. (1996, Science, 273, 5277)
“Search for Past Life on Mars:
Possible Relic Biogenic Activity in Martian Meteorite ALH84001”

• Nanofossils! 20 – 100 nm.
• Biogenic magnetite.
• Amino acids and polycyclic aromatic hydrocarbons (PAHs).

➔ Sensational claims!
➔ But each item has other, more mundane, possible explanations: natural features, contamination, etc.

➔ Does not meet the “Extraordinary Evidence” threshold. Currently, the jury is still out…
Mars in summary

- Mars is Earthlike: it has and had significant amounts of water.
- Mars is Moonlike (craters, not much erosion).
- Detecting life is problematic:
  - Difficult to find if it is there (chemical tests, etc.).
  - Concerns about contamination from spacecraft.
  - If DNA based life is found and spacecraft contamination ruled out, there could have been contamination via panspermia:
    - e.g. life on Mars first, then transported to Earth via meteorites.
  - If not DNA based, then panspermia can be ruled out, and an independent case is established.
Mars in summary

• Mars is confusing!
  The more we know, the more questions we have.

• Need to be very careful in Mars science to prevent “wishful thinking” from coloring interpretations.
  – Was Mars ever warm and wet? Maybe not.
  – Shouldn’t assume everything behaves like the Earth (e.g. obliquity, polar wander, Gyr timescales).

• At what point is it appropriate to give up the search for life?
  – Can’t prove the nonexistence of life on Mars!
  – It is costly to sterilize landers.
  – Astronauts would contaminate the planet.
The lineup of solar system suspects in the search for life

Mars
Europa
Enceladus
Titan
Other habitable zones in the solar system?

- Europa: icy crust, tectonic-like features, liquid ocean below.
- Enceladus: Polar jets provide evidence for liquid underground lake? Ocean?
- Titan: high-pressure atmosphere, methane lakes.
Search for Life’s Beginnings

Iris Fry

The scientific field devoted to the origin of life on Earth is very young, having taken its first experimental steps in the 1950s. Though the question has captivated human imagination since the dawn of history, its scientific pursuit has depended on several crucial conceptual developments during the 20th century. First, the emergence of life had to be conceived of as an integral part of the general process of evolution, leading from the geochemistry of the barren Earth to the universal common ancestor, which later diversified into the Darwinian tree of life. Following the rise of molecular biology in the 1950s and 1960s, the origin-of-life question could be formulated in biochemical and genetic terms, making it a subject of experimental investigation.

Early on, most scientists engaged in this research were chemists who attempted to formulate plausible scenarios for the prebiotic synthesis of organic building blocks, biochemically relevant polymers, and the first metabolically or genetically functional chemical structures. In the late 1970s, however, geologists also became increasingly involved in the field. Their participation was associated with the rise of a new paradigm positing that the synthesis of organic building blocks and the emergence of life itself took place not in the “primordial soup” of the traditional hypotheses but in the vicinity of underwater hydrothermal vents, at high temperature and under extreme pressure. Supporters of this new conception claim that origin-of-life theories can now be subjected to more rigorous constraints posed by specific primordial physical settings (1). On the other hand, the “soup people”—in particular, Stanley Miller, renowned pioneer of the 1953 prebiotic simulation experiments, and his colleagues—reject the alternative paradigm as empirically untenable (2).

In Genesis, Robert Hazen tells the story of these debates over the origin of life. There is no one better suited to examine recent developments in the experimental study of the topic. Trained in mineralogy and crystallography, he has been personally involved in the major lines of research through which Earth scientists have come to shape the field. Describing these contributions, he vividly portrays numerous experiments and observations. Hazen’s academic home, the Geo-physical Laboratory at the Carnegie Institution of Washington, which specializes in investigations of chemical reactions under extreme conditions, serves as an ideal setting for his experiments on the effects of high pressure and temperature on organic synthesis and particularly on the possible role of minerals abundant in hydrothermal vents in such synthesis. Describing the scientific status of this lab, its remarkable members, and their close professional and personal relationships, Hazen weaves the scientific and the personal into an engaging, sometimes dramatic tale. He highlights the excitement involved in research, the many setbacks and disappointments, and the inevitable internal politics within the origin-of-life community. In addition, his research team’s membership in the NASA Astrobiology Institute allows him to comment on the role of geologists in the study of possible conditions for life on Earth and other extraterrestrial sites within the context of the new “deep-origin” paradigm.

An underlying theme of the book is Hazen’s conception of the origin of life as part of a wider “theory of emergence” (3), a perspective based mainly on the ideas of theoretical biologist Harold Morowitz, a colleague of Hazen’s at George Mason University. According to this ambitious theory, the growth of organization and complexity in physical, chemical, biological, and social systems follows a general, though as-yet-unknown, principle on a par with the universal laws of nature. Considering the origin of life as a quintessential process of emergence, Hazen suggests that uncovering “the missing law” should advance origin-of-life research. However, although various complex systems do share common features, the “new science of emergence” is in danger of downplaying the unique features of living systems as well as the distinction between physical and chemical selection on the one hand and natural selection on the other. Moreover, as Hazen acknowledges, the basic concepts underlying this grand scheme (e.g., complexity) are far from clear. Since the origin-of-life field itself lacks firm, unequivocal conclusions, it is doubtful whether such additional conceptual baggage offers much scientific value.

Among the many issues dividing the origin-of-life community, none is more crucial than the controversy between “RNA-first” and “metabolism-first” scenarios. This division stems from the difficulty of deciding which emerged earlier, genetic polymers or metabolic cycles. Because nucleic acids and protein enzymes are tightly interdependent in extant living cells, an adequate theory must establish how either could have originally functioned on its own. After describing the rival positions even-handedly, noting the pros and cons of both, Hazen commendably feels that he has to place his bets on the table. He comes down on the side of metabolism-first, probably in the form of a molecular layer on a surface of a rock. Interestingly, he bases his choice on the “theory of emergence” and the hypothesis that life emerged through stages of increasing complexity. But wouldn’t a primitive genetic system, made of RNA or a simpler genetic polymer, also have to emerge through such stages?

The chemical requirements for the establish-ment of a self-replicating genetic system under prebiotic conditions are clearly extremely complex. Nonetheless, the support for the RNA-first notion, despite its difficulties, reflects the double realization that the emergence of life’s com-

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Meteoroid Transfer to Europa and Titan
Gladman, Dones, Levison, Burns, Gallant 2006 LPS Conference

• “Via extensive numerical simulations, we calculate the delivery efficiency of terrestrial impact ejecta to Europa and Titan. We show that (perhaps surprisingly) in an averaged large-scale impact (KT-level) a few to a hundred terrene meteoroids reach Europa and Titan.”
Other habitable zones in the solar system?

- Europa: icy crust, tectonic-like features, liquid ocean below.
- Enceladus: Polar jets provide evidence for liquid underground lake? Ocean?
- Titan: high-pressure atmosphere, methane lakes.

Common thread: elliptical orbits; heating by tidal flexure of the satellites.
The Galilean Moons

L to R: Ganymede, Callisto, Io, Europa
(In order of distance from Jupiter: Io, Europa, Ganymede, Callisto)

From Galileo and Voyager spacecraft
Europa is \(~10\%\) smaller than our Moon
Europa: An Ocean World

- Second innermost Jovian moon.
- Icy crust over salty water ocean
  - \(~100\) km thick \(\Rightarrow\) 2x Earth’s oceans in volume.
- Heating by tidal flexing (eccentric orbit + Jupiter).
- Concerns about panspermia not as great.
- Spacecraft contamination a concern but mitigated by sterilization or avoidance (e.g. *Galileo* spacecraft diverted into Jupiter in 2003).
- Robotic sampling likely could only probe the ice layer. (Fossil frozen microbes?)
- Issue of intense particle flux from Jupiter’s magnetosphere.
The periods of the three inner Galilean moons are simple integer multiples of each other, maintaining their orbits as ellipses rather than circles, and hence setting them up for tidal heating.
Heating of Europa


- The orbital eccentricity of Europa is continuously pumped by its mean motion resonance with Io.

- Tidal flexing kneads Europa's interior and gives the moon a source of heat, possibly allowing its ocean to stay liquid while driving subsurface geological processes.

- The ultimate source of this energy is Jupiter's rotation, which is tapped by Io through the tides it raises on Jupiter and is transferred to Europa and Ganymede by orbital resonances.
Tidal effects are the result of the gradient or change with distance of the gravitational force.

Gravitational force goes as the inverse square of distance.

The tidal force goes as the inverse cube of distance.
Europa is 1.5 x farther from Jupiter than Io. It feels less than 1/3 the tidal force than does Io, and gets much less tidal heating.

➡️ Just enough for warm ice (top figure), or plenty for a liquid ocean (bottom figure)?
Tidal amplitudes

- Earth: lunar ~ 0.54 m, solar ~ 0.25 m. Also: rotational bulge: 43 km at equator.
- Europa: 20 – 30 m (0.6 m if no ocean).
- Ganymede: 3 – 4 m (0.2 m).
- Callisto: 2 – 3 m (0.1 m).
- Titan: hundreds of m (including rotational forcing).
Galileo discovered a liquid water layer under the surface of Jupiter’s moon Europa in 1998.

Galileo images showed weird ice geology: plates of ice broken apart and rotated.

→ Circumstantial evidence for an ocean, past or present.
Ice Rafts on Europa

Enhanced-color view of part of Conamara Chaos, showing ice rafts up to 10 km (6 mi) across. White areas are ejecta from the crater Pwyll.
Pwyll

One of the youngest features on Europa:
• 26 km across.
• Central peak ~600 m high.
• Water ice.
Active formation of ‘chaos terrain’ over shallow subsurface water on Europa

B. E. Schmidt1, D. D. Blankenship1, G. W. Patterson2 & P. M. Schenk3

Europa, the innermost icy satellite of Jupiter, has a tortured young surface1–4 and sustains a liquid water ocean1–6 below an ice shell of highly debated thickness1–5,7–10. Quasi-circular areas of ice disruption called chaos terrains are unique to Europa, and both their formation and the ice-shell thickness depend on Europa’s thermal state1–5,7–17. No model so far has been able to explain why features such as Conamara Chaos stand above surrounding terrain and contain matrix domes10,18. Melt-through of a thin (few-kilometre) shell3,7,8 is thermodynamically improbable and cannot raise the ice10,18. The buoyancy of material rising as either plumes of warm, pure ice called diapirs1,9–15 or convective cells16,17 in a thick (>10 kilometres) shell is insufficient to produce the observed chaos heights, and no single plume can create matrix domes10,18. Here we report an analysis of archival data from Europa, guided by processes observed within Earth’s subglacial volcanoes and ice shelves. The data suggest that chaos terrains form above liquid water lenses perched within the ice shell as shallow as 3 kilometres. Our results suggest that ice–water interactions and freeze-out give rise to the diverse morphologies and topography of chaos terrains. The sunken topography of Thera Macula indicates that Europa is actively resurfacing over a lens comparable in volume to the Great Lakes in North America.

Although the setting in different astrophysical environments may

“Chaos terrain (or chaotic terrain) is an astrogeological term used to denote planetary surface areas where features such as ridges, cracks, and plains appear jumbled and enmeshed with one another.” (Wikipedia)
A melt lens below Thera Macula has the equivalent of the Great Lakes’ water.
More unusual geology—fractures overlying fractures.

Evidence for a thin, active crust.
Magnetic field measurements:

Europa has an induced magnetic field as it plows through Jupiter’s magnetic field.

This requires a highly electrically conducting layer beneath Europa’s ice crust—salty water. Smoking gun for a salty subsurface ocean!
These “cycloidal fractures” say thin (hundred meters) ...

... this impact crater, 30 km across with a peak 600 meters high, says thick (10 km).

But we still do not know how thick the ice crust is.
Evidence for a core is based on gravity measurements from spacecraft.

“Europa has emerged as one of the top Solar System locations in terms of potential habitability and possibly, hosting extraterrestrial life. Life could exist in its under-ice ocean, perhaps subsisting in an environment similar to Earth's deep-ocean hydrothermal vents or the Antarctic Lake Vostok. Life in such an ocean could possibly be similar to microbial life on Earth in the deep ocean. So far, there is no evidence that life exists on Europa, but the likely presence of liquid water has spurred calls to send a probe there.”
The blue-white terrains indicate relatively pure water ice, whereas the reddish areas contain water ice mixed with hydrated salts, potentially magnesium sulfate or sulfuric acid.
Exploring Europa

Where’s your landing site?
Where do you set up the drill?
To which ridge do you anchor?

We’re not ready to get down into the ocean.

← Europa at 6 m resolution (bottom of image)
Exploring Europa

A Europa Orbiter or “Clipper” (close flyby mission) is required to determine the thickness of the crust and identify landing sites.

➔ NASA/ESA mission, launch in 2020s.
➔ Multiple close fly-bys.
Deinococcus radiodurans: a bacterium tolerant to radiation.

Jupiter’s intense radiation environment makes even robotic exploration difficult.
Cassini-Huygens: 3 tons of discovery power; 11 years of a remarkable Saturnian odyssey.
Enceladus

- Sixth largest moon of Saturn: 505 km diameter.
- A scaled-down version of Europa?
- Icy, with evidence for subsurface liquid water.
  → Plumes/geysers deliver sodium-rich gas to Saturn’s E ring.
  → Heating from tidal flexing, radioactivity, and possibly energy release from methane clathrates.
- Easier to explore than Europa (radiation, gravity).
Images from Cassini reveal a geologically young surface.
Enceladus Plumes

2005: Cassini discovered plumes and a south polar fracture system.
IR image (12-16 μm) shows hot stripes.

~ 150 km long fractures.
Heating of Enceladus

Liquid water, cryovolcanism

⇒ Internal heat source.

Is tidal heating enough?

⇒ Mimas is closer to Saturn, and has a more eccentric orbit, but appears geologically dead.

⇒ Some combination of tidal heating, radioactivity, other sources.
Organics in the Plumes

2008: Cassini discovers organics, ammonia in the plume by flying through plume and analyzing the material with its neutral mass spectrometer.

2009-2011:

- Cassini finds NaCl, NaHCO$_3$, Na$_2$CO$_3$ salts are the most abundant non-water constituents in the plume particles (Postberg et al. 2009, 2011)
- High heat flow from the south polar region measured by Cassini (Spencer et al. 2009)
2014: Cassini discovers a regional sea beneath the South Pole. Beneath the jets is a region of liquid water, potentially stable for very long time periods.

Iess et al., 2014. Science
Silica Nanoparticles in the E-ring

2015: Cassini finds silica nanograins in the E-ring, indicative of hydrothermal systems (Hsu et al., 2015).

Laboratory experiments indicate that these dust particles must have formed on the seafloor at temperatures above 90°C (194°F) suggesting that seafloor hydrothermal activity is occurring.

The salts are concentrated in the largest ice grains in the plume, at a concentration ~ 0.5-2% by mass relative to water.

This is consistent with the environment required for the silica nanograin of < 4% salts, and close to terrestrial seawater (3.5%).
Warm, low-density material rising to the surface from within, in its icy shell (yellow) and/or its rocky core (red).

The "salty" composition of plumes strongly suggests that its source is a subsurface salty ocean or subsurface caverns filled with salty water.[59] Alternatives such as the clathrate sublimation hypothesis can not explain how "salty" particles form. [58] Additionally, Cassini found traces of organic compounds in some dust grains.[58] Enceladus is therefore a candidate for harboring extraterrestrial life. [60]
Life within Enceladus?

Multiple factors make the idea that life might exist there plausible:
- An accessible, salty ocean.
- Organics.
- Nitrogen.
- Energy.
- Hydrothermal activity.

How would you investigate?
Last Flyby through Enceladus’ Jets

- Flyby date: October 28, 2015
- 50-km closest approach
Mass spectrometers of much higher resolution, range, sensitivity can now be flown.
• Fly through the Enceladus plume just like Cassini did....

• But do it with instruments of today’s capabilities...Cassini instruments are 20 years old.