A1199
Are We Alone?
The Search for Life in the Universe
Summer 2019

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Start outlining projects!
Now: Habitable zones in the Solar System
A definition for life?

NASA effort to create a “working definition” for their Exobiology and Astrobiology research programs:

Life is “a self-sustaining chemical system capable of Darwinian evolution.” (Joyce, 1994)

→ Concise!
→ “Self sustaining” and “evolving”.
→ Too specific? Un-observable?
What is life?

1. A self-organized non-equilibrium system such that

2. its processes are governed by a stored symbolic program and

3. it can reproduce itself, including the program.

From: Smolin, The Lives of the Cosmos, p. 156
Alternative Biochemistries?

- Alternative chirality molecules:
  Terrestrial: L amino acids, D sugars

- Non-carbon based biochemistry?
  “Carbon chauvinism”.
  Silicon biochemistry (‘organosilicon’)?

  - Si less versatile than C; cannot form double bonds (so no analog to carbonyl group compounds).
  - SiO$_2$ = analog to CO$_2$ but does not dissolve in water.
  - Carbon cosmically more abundant 10:1, but less abundant in Earth’s crust. Yet life is carbon based.
  - But … c.f. silicate skeletons of *diatoms*.

Alternative Biochemistries?

Other exotic element bases:

→ Chlorine as an alternative to oxygen (electron receptor).
→ Arsenic as an alternative to phosphorus: some microbes metabolize As.

Non-water solvents?

→ Ammonia: not as versatile as water in ability to form both acids and bases (bonding properties); temperature range: 195 to 240 K.
→ Methane CH₄: Titan? (91 to 112 K.)
→ Hydrogen flouride (HF).

The lineup of solar system suspects in the search for life

- Mars
- Europa
- Enceladus
- Titan
Titan: A New World
Titan

- Second largest moon in the solar system.
  (Jupiter’s Ganymede = largest; our Moon = 5th)
- Ni-rich atmosphere, 4x denser than Earth’s.
- Equatorial dunes of organics carved into water-ice landscape.
- Water is frozen out, but liquid methane and ethane lakes have been identified at high latitudes.
- An opportunity to search for a different basis of life; e.g., methanogens.
Titan

IR images from Cassini, Nov 2004 (3 bands)
Titan

→ “True color” imaging from Cassini (3 bands, 2012).
→ Note recently formed vortex near South pole, as well as atmospheric haze.
Titan models: fully differentiated interior

Titan Interior, Tobie et al., 2006
C/MR² = 0.32-0.33

Titan Interior, Castillo and Lunine, 2010
C/MR² = 0.342
Lakes on Titan

Titan Specular Glints

Campbell et al, 2003
Imaging from Cassini and the Huygens probe dropped into Titan
Huygens touchdown site
Titan’s Atmosphere

NB – 1D radiative transfer codes are able to produce matching temperature profiles by including what we know about Titan’s composition.
GCMS measurements from Huygens: Methane, acetylene, ethane, carbon dioxide are evaporating from the surface.

Niemann et al 2005, 2010
Post-landing vaporization of methane from beneath the probe

Constant mixing ratio of methane up to 7 km altitude followed by decrease to cloud base

Decline in the methane mixing ratio along a saturation vapor pressure curve

Huygens GCMS results (Niemann et al., 2010)
Dunes on Titan surface

Fig. 4. Plot of dune coverage on Titan as seen in Cassini Radar swaths. All regions on Titan containing a high proportion of dunes as seen in SAR swaths (T through T28) are outlined in dark green. Swaths are delineated by flyby number and are labeled close to the major dune areas. Dune-populous areas occur at Titan’s equatorial regions.

Fig. 5. Dunes in the T8 Belet seas (top, ∼260°W, 5°S) and the T17 Fensal seas (bottom, ∼500°W, 10°N). Both regions are effectively covered in dunes that are closely spaced and highly parallel. Dunes devolve around mountains and other topographic features, and they create a broadly continuous pattern in the T17 image. Radar-bright, underlying substrate can be seen between some dunes, in particular, close to topographic obstacles in the T17 region. In the lower left corner of the T8 image, bright lineations associated with the dunes are radar backscatter returns indicating steep, uprange faces.

Images obtained October 2005 and September 2006, ∼300 m resolution, north is up, arrows indicate direction of radar illumination for each with incidence angle contained.
Ligeia Mare: one of Titan’s great seas
Together RADAR, VIMS, and ISS provide a complete picture of the lake / sea distribution.

<table>
<thead>
<tr>
<th>Lake Feature</th>
<th>Global</th>
<th>North (55°N-90°N)</th>
<th>South (55°S-90°S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath Coverage</td>
<td>59%</td>
<td>81%</td>
<td>67%</td>
</tr>
<tr>
<td>Filled / Partially Filled / Empty</td>
<td>1.1% / 0.1% / 0.3%</td>
<td>12% / 0.9% / 1.3%</td>
<td>0.3% / 0.1% / 1.2%</td>
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Lacustrine, fluvial, and hillslope morphologies express a range of characteristics that suggest a rich history operating over seasonal, millennial, and geologic timescales.

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<td>0.3% / 0.1% / 1.2%</td>
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</table>
Loss of liquid of \( \sim 86 \text{ km}^3 \), avg. depth 5 meters \( \rightarrow \) 5 m layer lost over 5 years.
Destruction of methane

~$10^7$-$10^8$ years

Stratosphere

Troposphere

~10 years, 10,000 years

~10-100 years
Low latitude methane storms

Polar lakes/seas

Too dry for lakes

Polar lakes/seas

Too wet for dunes
Familiar Physics in Unfamiliar Environments: Studying the Processes that Shape Planetary Surfaces
Aeolian Processes
Fluvial Processes

Narrow, sinuous, radar-bright channels on the western portion of Xanadu extend for many hundreds of km. They may be river networks of methane that carry photochemical debris as sediment (image is ~ 80 km wide).

This southern-hemisphere “coastline” resembles terrestrial embayments and wetlands (~ 100 km wide).

Networks of channels/valleys with high tortuosity near Menrva (T3) appear to drain $> 10^4$ km$^2$ into radar bright (rough?) regions (image is ~ 60 km wide).
Lacustrine Processes
Pluvial Processes

Turtle, Science 2011
Impact Cratering
Endogenic Processes?

Kirk, LPSC 2011
The importance of water for life

Liquid water plays a major role in the rapid formation of life and its evolution:

• Provides a good compromise between mobility of molecules and rate of interaction (density).
• Polar; excellent solvent for salts.
• Stays liquid over a wide range of temperatures.
• Interesting properties: Expands when freezing; Slippery; Wet; High heat capacity.

⇒ Host liquid for all the biochemistry we know of.
Could methane and ethane work?

Methane and Ethane as a liquid medium for biochemistry:

• Allows organic molecules to hydrogen-bond.
• Polar hydrocarbons associated with the liquid might create “insides” and “outsides” in liquid ethane/methane.
• “Biological” molecules would be dominated by C-N bonds rather than C-O as on Earth.
• Some C-O compounds resulting from interaction with water-ice bottom.

Would be very different from “life as we know it”.
Titan has a big advantage for astrobiology

• Life in ethane-methane seas on Titan is a far more stringent test of a separate, second origin than life found on Mars, Europa, or Enceladus.
• Impact exchange of material between bodies in our solar system implies a fundamental difficulty in proving that life “like us” had a separate origin.
• Life in a hydrocarbon sea is so fundamentally different – at the molecular level – that it immediately would imply a second, separate origin of life.
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\[ \text{C, H, O, N, P...} \]

? Titan

Elements
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- Life in a hydrocarbon sea is so fundamentally different – at the molecular level – that it immediately would imply a second, separate origin of life.

- No planetary protection issues: landing in the hydrocarbon lakes sterilizes the probe.

- Easy access to the lakes:
  no radiation, no drilling, just repeat Huygens mission....
“If life is an intrinsic property of chemical reactivity, life should exist on Titan.”

“Indeed, for life not to exist on Titan, we would have to argue that life is not an intrinsic property of the reactivity of carbon-containing molecules under conditions where they are stable.”

Three interesting observations

1. A low abundance of ethane at the surface.
2. \( \text{C}_2\text{H}_2 \) (acetylene) surface abundance < \( \text{C}_6\text{H}_6 \) (benzene).
3. A surface sink of hydrogen (Strobel 2010).

1–3 together can be explained by a cycle which combines hydrogen with acetylene at the surface to re-make methane.

... or each item has a separate explanation.
Basic abiotic chemical reaction on Titan (possibly):

- Methane
- Ethane
- Acetylene
Titan surface reactions?

“Metabolism”
$\text{C}_2\text{H}_2 + 3\text{H}_2 \rightarrow 2\text{CH}_4$

+ 334 kJoules/mole
(McKay and Smith, 2005)

Chemistry
$3\text{C}_2\text{H}_2 \rightarrow \text{C}_6\text{H}_6$
Dragonfly: a drone on Titan
Dragonfly is a rotorcraft lander mission – part of NASA's New Frontiers Program – designed to take advantage of Titan's environment to sample materials and determine surface composition in different geologic settings.
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Dragonfly is a rotorcraft lander mission – part of NASA's New Frontiers Program – designed to take advantage of Titan's environment to sample materials and determine surface composition in different geologic settings.

- Sample surface material and measure with a mass spectrometer ➔ Identify the chemical components and processes producing biologically relevant compounds.
- Measure bulk elemental surface composition with a neutron-activated gamma-ray spectrometer.
- Monitor atmospheric and surface conditions, including diurnal and spatial variations, with meteorology sensors.
- Use imaging to characterize geologic features.
- Perform seismic studies to detect subsurface activity and structure.
- Contribute to atmospheric profiles.
- Provide aerial images of surface geology.
- Give context for surface measurements and scouting of sites of interest.
Dragonfly: a drone on Titan

- Dragonfly field demo, 2018.
- Launch by end-2025.
- Arrival at Titan in mid-2030s.
Radiative Balance in Habitable Zones

• Earth-equivalent radiation for a star with a different luminosity:

\[ \frac{L_\star}{r_{\text{equiv}}^2} = \frac{L_{\odot}}{r_{\oplus}^2} \]

• For thermal balance, radiation in = radiation out.

\[ 4\pi R_\oplus^2 \sigma T_\oplus^4 = \frac{1}{4} \frac{L_\odot R_\odot^2}{r_{\oplus}^2} \quad \text{or} \quad T_\oplus \propto \left( \frac{L_\odot}{16\pi\sigma r_{\oplus}^2} \right)^{1/4} \]

• So, to get a specific temperature, given a star with specific luminosity, need to be at a distance \( r \) such that:

\[ r = r_{\oplus} \left( \frac{L}{L_\odot} \right)^{1/2} \left( \frac{T_\oplus}{T} \right)^2 \quad \text{with} \quad r_\oplus = 1 \text{ AU} \]
## Stellar Types and Temperatures

### Table of Stellar Properties

<table>
<thead>
<tr>
<th>Class</th>
<th>Surface temperature (kelvins)</th>
<th>Conventional color</th>
<th>Apparent color</th>
<th>Mass (solar masses)</th>
<th>Radius (solar radii)</th>
<th>Luminosity (bolometric)</th>
<th>Hydrogen lines</th>
<th>Fraction of all main sequence stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>≥ 33,000 K</td>
<td>blue</td>
<td>blue</td>
<td>≥ 16 M⊙</td>
<td>≥ 6.6 R⊙</td>
<td>≥ 30,000 L⊙</td>
<td>Weak</td>
<td>~0.00003%</td>
</tr>
<tr>
<td>B</td>
<td>10,000–33,000 K</td>
<td>blue to blue white</td>
<td>blue white</td>
<td>2.1–16 M⊙</td>
<td>1.8–6.6 R⊙</td>
<td>25–30,000 L⊙</td>
<td>Medium</td>
<td>0.13%</td>
</tr>
<tr>
<td>A</td>
<td>7,500–10,000 K</td>
<td>white</td>
<td>white to blue white</td>
<td>1.4–2.1 M⊙</td>
<td>1.4–1.8 R⊙</td>
<td>5–25 L⊙</td>
<td>Strong</td>
<td>0.6%</td>
</tr>
<tr>
<td>F</td>
<td>6,000–7,500 K</td>
<td>yellowish white</td>
<td>white</td>
<td>1.04–1.4 M⊙</td>
<td>1.15–1.4 R⊙</td>
<td>1.5–5 L⊙</td>
<td>Medium</td>
<td>3%</td>
</tr>
<tr>
<td>G</td>
<td>5,200–6,000 K</td>
<td>yellow</td>
<td>yellowish white</td>
<td>0.8–1.04 M⊙</td>
<td>0.96–1.15 R⊙</td>
<td>0.6–1.5 L⊙</td>
<td>Weak</td>
<td>7.6%</td>
</tr>
<tr>
<td>K</td>
<td>3,700–5,200 K</td>
<td>orange</td>
<td>yellow orange</td>
<td>0.45–0.8 M⊙</td>
<td>0.7–0.96 R⊙</td>
<td>0.08–0.6 L⊙</td>
<td>Very weak</td>
<td>12.1%</td>
</tr>
<tr>
<td>M</td>
<td>≤ 3,700 K</td>
<td>red</td>
<td>orange red</td>
<td>≤ 0.45 M⊙</td>
<td>≤ 0.7 R⊙</td>
<td>≤ 0.08 L⊙</td>
<td>Very weak</td>
<td>76.45%</td>
</tr>
</tbody>
</table>

M Stars

- For an M star the luminosity ranges from $10^{-4}$ to 0.08 $L_\odot$
- Using $L = 0.01 L_\odot$ we get for the equivalent HZ (same range of surface temperatures for liquid water) using:

\[
r = r_\oplus \left( \frac{L}{L_\odot} \right)^{1/2} \left( \frac{T_\oplus}{T} \right)^2 \text{ with } r_\oplus = 1 \text{ AU}
\]

\[
0.08 \lesssim r_{HZ}(H_2O) \lesssim 0.18 \text{ AU}
\]

- At these radii, the planet is tidally locked to the star and it is more vulnerable to stellar flares.
Methane

- Now consider methane (CH$_4$) at standard atmospheric pressure for which the temperature range for the liquid state is approximately $91 \, \text{K} \leq T_{\text{liquid}} \leq 110 \, \text{K}$:

$$r = r_\oplus \left( \frac{L}{L_\odot} \right)^{1/2} \left( \frac{T_\oplus}{T} \right)^2$$

with $r_\oplus = 1 \, \text{AU}$

- Obtain a “methane habitable zone”:

$$0.92 \leq r_{\text{HZ}}(\text{CH}_4) \leq 1.6 \, \text{AU}$$
Methane HZ: stable over geologically long periods

- Situated at 1 AU—a quiescent region—avoiding the region of flares and tidal locking around M dwarfs.
- M dwarfs outnumber stars like the Sun by 10:1—these Titan analogs might be the most common type of “habitable” planet.
- M-dwarfs stay on the main sequence for longer than the age of universe …
  → Plenty of time for slow development of life.
- Spectroscopic bio-signatures—how observable would they be? An Earth-sized Titan would have a ratio of heat flow/stellar flux up to 30 times that of Titan today and 100 times that of the Archaean Earth.
Other habitable bodies in the solar system?

- Outer solar system is rich in water, and barely explored.
- Asteroids and comets have significant amounts of water – but do they have available energy sources?
Triton

- Voyager 2 mosaic, from one encounter in 1989.
- 7th largest moon and 16th largest solar system body.
- Nitrogen ice, frozen CO₂, frozen water.
Pluto / Charon

- Unexpectedly dynamic and active.
- Tholins (organic macromolecules) detected on Charon’s polar cap – from CH\textsubscript{4}, N\textsubscript{2}, etc.
Ceres

- Dawn, 2015
- Dwarf planet, 25% of mass of asteroid belt (but much smaller than Pluto, 14x).
- Bright reflective salts; also evidence for water.
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