In Situ Exploration of Titan’s Organic Chemistry and Habitability
A2202 Lecture 15: 28 October 2019

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Unique and compelling scientific opportunity

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• Places elsewhere in our Solar System provide pieces to the puzzle of the chemical processes that led to life.
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- We do not know how life came to form on Earth and cannot go back to study our own prebiotic history.
- Places elsewhere in our Solar System provide pieces to the puzzle of the chemical processes that led to life.
- Titan is the most like the early Earth and holds keys to understanding our chemical origins.

The largest of Saturn’s 62 moons

- First suggested by José Comas Solà (1908)
- Spectroscopic CH₄ detection by Gerard Kuiper (1944)

A satellite with an atmosphere
Titan's atmosphere is unique among satellites

- Ganymede
- Callisto
- Io
- Europa
- Moon
- Titan

Titan's atmosphere is denser than Earth's

- 2nd highest surface pressure of all solid bodies with atmospheres
- 1.5x pressure at Earth's surface

Seasons on Titan

- Saturn and Titan's year = 29.5 Earth years
- Saturn's axial tilt = 26.7°
- Titan's day = 16 Earth days

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
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<tbody>
<tr>
<td>Southern winter solstice</td>
<td>Oct 2002</td>
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<tr>
<td>Equinox</td>
<td>Aug 2009</td>
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<tr>
<td>Southern summer solstice</td>
<td>July 2017</td>
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<tr>
<td>Equinox</td>
<td>May 2025</td>
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<tr>
<td>Northern winter solstice</td>
<td>Apr 2032</td>
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<tr>
<td>Equinox</td>
<td>Jan 2028</td>
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Exploration of the Saturnian System

Northern Summer Solstice
Northern Winter Solstice
Northern Vernal Equinox

1 October 2019

Pioneer 11, Sept. 1979
Voyager 1, Nov. 1980
Voyager 2, Aug. 1981

Cassini Nominal Mission 2004–2008
Huygens Probe January 2005

Northern Summer Solstice
Northern Winter Solstice
Northern Vernal Equinox

October 2002

Northern Summer Solstice
Northern Winter Solstice
Northern Vernal Equinox

September 1979
November 1980
August 1981

Northern Summer Solstice
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October 2002

Northern Summer Solstice
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September 1979
November 1980
August 1981
Titan's surface revealed

- 1995: Hubble Space Telescope imaging (0.94 μm, Lemmon et al.)

Cassini-Huygens exploration

- 1995: Hubble Space Telescope imaging (0.94 μm, Lemmon et al.)
- 2004: Keck II Telescope using adaptive optics (∼1.6 μm, Roe et al.)
Cassini-Huygens exploration

- Saturn arrival, July 2004
- Huygens Titan descent and landing, Jan. 2005
- Cassini in Saturn orbit 2004 – 2017
  - 126 close Titan flybys

An ocean world

- Outer water-ice shell
- Global subsurface ocean
- Inner ice layer
- Silicate core, ~2000 km radius

Titan

- Diameter = 5150 km
- Surface gravity = 1.35 m/s² = 0.14 g
  - 14% of gravity at Earth’s surface
  - 83% of gravity at Moon’s surface
- Surface pressure = 1.5 bar
  - 1.5× pressure at Earth’s surface
- Surface temperature = 94 K = −290°F
  - Bedrock composition = water ice
Tectonic features

Angmar, Echoriath, Dolmed, Merlock, Gram Montes

28 October 2005

Mithrim Montes ~3,300 m (~10,900 ft)

28 October 2006

Signs of cryovolcanism

1 October 2019
Signs of cryovolcanism

Sotra Patera, 1.7 km (5500 ft) deep
Doom Mons, 1.45 km (4800 ft) high

Channels

North-polar lakes & seas
Clouds and weather patterns

- Methane cycle like Earth’s water cycle

![Clouds and weather patterns](turtle.png)

Huygens atmospheric descent, 2005

![Huygens atmospheric descent](huygens.png)

Titan’s complex organic chemistry offers a unique scientific opportunity

- Titan’s atmosphere supports rich photochemistry
- Organic material produced in the atmosphere covers the surface
- Potential for organic compounds to have mixed with liquid water
- Materials are easily accessible on the surface

![Titan’s complex organic chemistry](titan.png)
Titan’s organic complexity approaches Earth’s

Key ingredients necessary for life

• Energy
  - Sunlight, photochemistry
Key ingredients necessary for life

- Energy
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- Organic material
  - Abundant complex organics
- Liquid
  - Water
    - available at the surface in Titan's past
    - Interior ocean
- Two liquids
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  - Methane
    - Active methane cycle like Earth's water cycle
    - Liquid methane could support development of alternate biological systems
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    - active methane cycle like Earth's water cycle
    - Liquid methane could support development of extreme terrestrial variants

On Titan alone, can we study prebiotic chemistry in the full context of a planetary environment and Earth-like surface processes.

Titan offers the next step to answer fundamental questions

What makes a planet or moon habitable?
What chemical processes led to the development of life?
Has life developed elsewhere in our solar system?

Cassini revealed where to look for answers

- Diverse surface materials and environments
- Earth-like variety of geologic processes
- Science challenge is to get instruments to multiple high-priority sites to sample materials and measure compositions

Mobility is key for science measurements
Lander with aerial mobility enables wide-ranging in situ exploration

- Heavier-than-air mobility highly efficient at Titan (Lorenz 2000; Langelaan et al. 2017)
- Titan’s atmosphere 4x denser than Earth’s
  - reduces wingnut area required for lift
- Titan’s gravity 1/7th Earth’s
  - reduces power required
- Dragonfly retors function in well-understood flow regime, similar to that of stright aircraft, sailplanes, and wind turbines on Earth

Combines previous exploration strategies

- Helicopter (Lorenz 2006)
- Airship (helium or hydrogen; Levine & Wright 2005; Hall et al. 2006)
- Montgolfiere hot-air balloon (Roh et al. 2007)
- Airplane (Levine & Wright 2005; Sams et al. 2012)
- Sea lander (TMM proposal to NASA Discovery Program, Stratton et al. 2013)
- NASA Titan Explorer Flagship study (Leary et al. 2007)
  - Lander + Montgolfiere-balloon
  - Two balloons
  - Montgolfiere + lander

With both landed and aerial capability, Dragonfly accomplishes science objectives of multiple concepts using current technologies.
Mission elements

- MMRTG power
  - Charge battery used for flight and science activities
  - Waste heat maintains nominal thermal environment in lander

- Direct-to-Earth communication
  - HGA articulation used to target cameras to build up panoramas of surrounding terrain

- Science measurements on surface and in flight
  - Aerial imaging
  - Atmospheric profiles

Landed configuration and payload accommodation

- MMRTG power
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Mission timeline

- Launch in 2026 → Titan arrival in 2034
  - Direct atmospheric entry
  - Similar latitude and same time of year as descent of Huygens probe
Initial landing site provides access to multiple geologic settings

- Dunes
- Interdunes
- Impact crater deposits
- Access to sample organic sediments and materials with a water-ice component

Exploration strategy

- Over 2.5 years of exploration
  - ~60 Titan sols of science operations
  - Traverse distance up to ~180 km
  - Exploration of ≥24 unique sites

- "Leapfrog" exploration strategy to scout future landing sites
- 16-day Titan sols ⇒ relaxed operations schedule
  - Most of time is spent on the surface making science measurements

Comparison of candidate landing sites
Multidisciplinary science measurements at dozens of potential landing sites

- Prebiotic chemistry
  - Analyze chemical components and processes at work that produce biologically relevant compounds

- Habitable environments
  - Measure atmospheric conditions, identify methane reservoirs, and determine transport rates
  - Constrain processes that mix organics with past surface liquid water reservoirs or subsurface ocean

- Search for biosignatures
  - Search for chemical evidence of water- or hydrocarbon-based life

DraMS: Mass Spectrometer
- DrACO: Drill for Acquisition of Complex Organics
  - GSFC, Honeybee – MSL, SIA, ExoMars MOKA
- DraGN5: Gamma-ray Neutron Spectrometer
  - APL, LLNL, MESSINGER-5P5, Psyche GNS
  - GSFC, Schlumberger – Pulsed Neutron Generator
- DraGNet: Geophysics & Meteorology Package
  - APL sensor suite + NASA Lunar Mass Spectrometer
- DragonCam: Camera Suite
  - MSSS – OSIRIS-REx, Mars 2020

Comprehensive study of the chemical complexity and diversity of Titan’s solid surface

- Sample surface materials for detailed chemical analyses with the Dragonfly Mass Spectrometer
Comprehensive study of the chemical complexity and diversity of Titan’s solid surface

- Sample surface materials for detailed chemical analyses with the Dragonfly Mass Spectrometer

Complementary sample analysis modes:
- Gas Chromatography MS: Definitive molecular detection, chirality
- Pyrolysis: An alternate approach for detecting complex CHN compounds
- Laser Desorption: MS, a sensitive technique for studying volatile organics

Classification of surface materials at every site

- Measure bulk elemental surface composition
- Classify surface material
- Detect minor inorganic elements
- Reveal near-surface stratigraphy

Figure 4.1.6: Molecular Weight (Da) vs. Enantiomeric Excess (%) for Selected Amino Acids. Molecules such as amino acids can exist in either of two configurations (enantiomers: D and L).

Some compounds employed in Earth’s biochemistry – for example, sugars and most amino acids – are chiral. Chiral compounds can exist in either of two configurations (enantiomers: D and L). In meteorites, the D and L forms are generally also present in approximately equivalent amounts, although excesses of the L enantiomer ranging from 1–15% have been observed among the amino acids from meteorites. This chiral excess in amino acids can be a result of non-biological processes, such as abiotic synthesis in space. For instance, in the Tagish Lake Meteorite, unusually large L-enantiomeric excesses ranging from 43–45% were reported, with up to 21% for the non-proteinogenic amino acid isovaline. In an analysis of amino acids from meteorite 10055, significant enantiomeric excesses ranging from 10–45% were observed, with up to 21% for the non-proteinogenic amino acid isovaline. In contrast, biological materials on Earth in multiple different amino acid types would be expected to have a homochiral structure (same chirality). This suggests that such homochirality is required for the proper folding and function of proteins in biochemistry across the three domains of life on Earth. For this reason, it is suggested that life on Earth may have originated from extraterrestrial sources.
Meteorological and seismological monitoring of an ocean world

- Monitor atmospheric conditions, identify CH₄ reservoirs, and determine transport rates (T, P, CH₄, wind speed & direction)
- Constrain regolith properties (e.g., porosity)
- Thermal diffusivity, dielectric constant
- Constrain processes that mix organics with past surface liquid water or subsurface ocean

Meteorological and seismological monitoring of an ocean world

- Detection and characterization of seismic activity
- Variation with orbital phase

Characterize landforms and surface processes in multiple geologic settings

- Forward, Downward, Microscopic
- LED illuminated mixture of water ice (white) and two tholin flavors: orange + yellow
- RGB = 0.935, 0.770, 0.455 μm
- Panorama
- 2 mm × 2 mm × 2 m × 20 cm
Characterize landforms and surface processes in multiple geologic settings

Aromatic organics, especially PAHs, exhibit fluorescence when stimulated by near-UV light

Advantages of Titan’s environment

- Dense atmosphere
  - Enables aerial mobility
  - Extended time during EDL
  - Pneumatic sampling
  - Protection from radiation
- 16-day T/ol / orbital period
  - Relaxed operations schedule
  - Dense atmosphere + length of day → calm conditions
    - Characterized by Cassini-Huygens, Dragonfly
- Low T → passive cooling
  - Maintain samples (DrACO, DraMS) and sensors (DraGNS) at cryogenic Ts

Advantages of Titan’s environment
Exploration and discovery on an ocean world to determine how far chemistry has progressed in environments providing key ingredients for life

Sharing the adventure

- Broad range of disciplines
  - Multi-investigator Cassini-Huygens analysis
  - Lab work, e.g., generating dusts for testing
  - Testing sample acquisition and transfer
  - Instrument and system development and testing, test design, CFD modeling
  - Aeronautics: wind-tunnel and flight testing, rotor design, CFD modeling
  - VR/AR simulations for spacecraft design and planning and executing operations
- Opportunities for engagement
  - NASA Participating Scientist Program
  - Complementary Dragonfly Student and Early Career Investigator Program
  - Community workshops and meetings at scientific conferences

http://dragonfly.jhuapl.edu
Initial landing site provides access to multiple geologic settings

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(Griffith et al., 2019)