Outer Planet Satellites Extreme (Habitable?) Environments

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Ground vs Space

Earlier Missions
- Pioneer 10 and 11
  - First close up of Jupiter (1973)
    - Last contact P11 on 1/22/2003, and for P10 in 2/2003
- Voyager
  - 4-planet tour – window every 175 yr
  - Launch 2 spacecraft in 1977
  - Nominal 5 year mission

The Galileo Mission
- Mission profile
  - L: 10/18/1989 on Atlantis
  - Venus, Earth, asteroid flybys & comet crash
  - 23 month prime mission tour of the satellites
  - 14 year mission ends 9/17/03
  - Crashed into Jupiter to prevent astrobiological contamination
- Spacecraft
  - 11 instruments + atm probe
  - Mass 2.5 tons
  - Powered by Plutonium

Where are Voyagers Now?
- Termination shock
  - Solar wind forms an expanding bubble in space
  - Where the interstellar gases slow the solar wind and flow around it: termination shock
  - Mission should continue until at least 2020
- Timeline
  - Voyager 1 hit the termination shock at 94 AU in 2004
  - Voyager 1 reached 120 AU 8/06
  - Voyager 2 hit the termination shock at 84 AU on Aug 30, 2007
  - Heliosheath is not symmetric—smaller where V2 left the SS

Voyager Images
- Io
- Europa
- Ganymede
- Callisto
Jovian Moons & Tidal Heating

- Orbital period length depends on orbit size
  - 3 inner Galilean moons in orbital resonance
    - \( P_{\text{Europa}} = 2P_{\text{Io}} \)
    - \( P_{\text{Ganymede}} = 2P_{\text{Europa}} \)
    - Resonance keeps orbits eccentric → tidal heating.
- Tidal heating: \( F_{\text{tide}} = G\frac{Mm}{r^2} \)
  - Differential tide raising force
  - Heating is far greater on a closer moon
- Callisto is not in resonance
  - No tidal heating

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Satellite Details

- Diameter 3,138 km – smallest Galilean moon
- \( T_{\text{surface}} = 128K \)
- \( \rho \approx 3,018 \text{ gm cm}^{-3} \)
- Gravity = 0.135 \( g_{\text{Earth}} \)

Europa’s Ductile Surface

- Chaos region
- Volcanos
- Crater Pwyll
- Ridges & Domes
- Ridges & cliffs

Moons Sizes

- Enceladus
- Europa
- Callisto
- Titan
- Triton
- Ganymede

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2/23/95 – HST finds \( \text{O}_2 \) in atmosphere

- \( P = 10^{-14} \text{ atm (bar)} \)
- Sputtering from impacts of high energy particles in Jupiter’s magnetosphere → \( \text{H}_2 \) vapor
- Photo-dissociation
- Escape of \( \text{H}_2 \)
- Scale height \( H \approx 125 \text{ km} \)

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- Used radio occultation
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Europa
Liquid Ocean Interior

- 12/16/97 200km flyby
- Intense geological transformation (tectonic plates)
- Suggests liquid ocean
- Interior heating
- Fractures may allow transfer between surface & ocean

Discovering Europa’s Ocean

- Early evidence
  - Spectrum in 1957 – showed water ice
- Voyager and Galileo
  - Images show many tectonic features showing interior processes
  - Galileo flyby slightly altered gravity field implied a high density core, a mantle and an outer region 150 km of something at 1 gm/cm³
- Changing magnetic field – there has to be a conducting layer
  - Jupiter’s magnetosphere rotates ~ 10 hrs; Europa moves through the magnetosphere
  - This time varying B field creates a Bfield in a conductor which was observed on Europa
  - Likely conductor: salt water
    - Depth < 175 km, ice shell thickness 4-16 km

Europa – Internal Activity

- Icy crust thickness estimate
  - 19-27 km
  - Complex craters larger than 27 km – have no height
  - Lack of support

Intense Radiation

- Intense radiation environment → chemistry on surface
- Oxygen and Sulfur dominate particles hitting surface
- This can penetrate through cracks
- Sulfur implantation can redden surface in 40 yrs
- May provide on the surface a source of electron acceptors

Comparison to Earth – Astrobiology Link

- Earth Deep Sea Hydrothermal systems
  - Host novel bio communities
  - 60,000 km long: flanks, ridges, subduction zones
- Key role in origins of Earth life
  - Hot, reducing conditions like early earth
  - UV protected; refuge from bombardment of planetesimals
  - Abundant source of electron donors (e.g. H₂)
  - Presence of electron acceptors (e.g. seawater SO₄²⁻, Fe³⁺ from mineral hydrolysis)
**Ganymede**

- **Satellite Details**
  - 3rd farthest orbit from Jupiter
  - Largest satellite in SS – larger than Mercury
  - Galileo detects internal magnetic field
  - Molten iron core (dynamo)
  - Open/closed field line boundary delimits bright polar caps.
  - Interaction with magnetosphere → conducting layer (ocean) – much deeper than on Europa (at least 200 km depth)

- **Tenuous atmosphere (exosphere)**
  - 10/10/95 – HST discovery of H, O, O₂, O₃
  - Scale height H = 100-1000 km
  - Source: Magnetospheric particle sputtering & photolysis and sublimation from surface

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**Ganymede’s Strange Surface**

- **Dark Terrain**
  - Old, heavily cratered
  - Covers 40% of surface
  - Tectonic forms

- **Bright Terrain**
  - 60% of surface, covered in grooves up to 700 m high
  - Rift tectonics – tensional faults
  - Icy volcanos

- **Craters**
  - Large variety in icy surface

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**Callisto – Improving Resolution**

- **Satellite details**
  - Orbits farthest from Jupiter
  - Second largest Galilean satellite
  - Heavily cratered (old) surface
  - Detection of atmosphere (exosphere)
    - Pressure ~ 7.5 x 10⁻⁶ bar
    - CO₂ and H₂ (from sputtering of CO₂ ice on the surface)
  - Detection of liquid conducting layer (ocean)
    - At perhaps at 135-150 km depth
    - Ocean thickness ranges between 120-180 km
Ganymede & Callisto Composition

- Ices
  - Crystalline & amorphous water
- Dark materials
  - Clays
  - Organics (CN, CH)*
  - Hydrated sulfates
- Volatiles
  - O₂, O₃, CO₂, SO₂

Summary of Galilean Satellite Interiors

- Ices
- Crystalline & amorphous water
- Dark materials
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The Cassini Mission

- Timeline
  - Launch 10/13/97
  - Arrival July, 2004
  - Huygens probe tour 12/25/04
- Goals
  - Probe to Titan surface
    - Chemical analysis of atm
    - T, P and º of atmosphere vs altitude
    - Surface properties
  - Orbiter
    - Radar images of titan (200m res)
    - Imaging & radar of other moons
    - Rings – physical properties
    - Comp of Saturn atmosphere
    - Magnetosphere-ring interaction
  - Asteroid flyby

Instrumentation

- Rich array of science experiments
  - Imaging Science subsystem
  - UV spectrometer
  - Visual/IR mapping spectrometer
  - Microwave spectrometer
  - IR spectrometer
  - High speed photometer
  - Titan radar mapper
  - Radio science subsystem
  - Dust analyzer

Saturn’s Family – Voyager

- Rhea
- Enceladus
- Tethys
- Mimas
- Iapetus
- Dione
- Dione's North Pole View
- Cassini - Saturn Orbital Sample Tour
- Sample Cassini orbit tour through the satellites
Saturn’s Family – Cassini

Dione  Rhea  Iapetus

Enceladus  Tethys  Mimas

Saturn’s Family – Cassini

Satellite specifics
- Orbits Saturn 3.6x10^6 km
- Diameter: 1660 km
- Large impact basin 575 km in diameter

Hemispherical dichotomy
- Leading: albedo 5%
- Trailing: albedo 50%, water and ammonia ice
- Rotation is in synchronous rotation

Source:
- Internal?
- External – debris from Phoebe?
- Magnetosphere – charged particles?

Iapetus Dichotomy

Iapetus Dichotomy

Dark Side of Iapetus

- Close up of dark carbonaceous material on top of water ice
- N-facing craters are coated

Equatorial Ridge

- Covers 1/3 of circumference: 1300 km
- 20 km high in places
- Image range: 123,000 km

Source:
- Internal?
- External – debris from Phoebe?
- Magnetosphere – charged particles?
**High Resolution Satellites**

- Tethys (false color)
- Enceladus

**Enceladus Atmosphere & Saturn’s Magnetosphere**

- **Discovery of Atmosphere**
  - 2/17/05 – magnetometer detects bending of Saturn’s magnetosphere near Enceladus
- **Composition:** $\text{H}_2\text{O}$ (91%), $\text{N}_2$ (4%), $\text{CO}_2$ (3.2%), $\text{CH}_4$ (1.7%)
- **Enceladus radius ~ 250 km**
- Thought too small to hold atm
- Suggests resupply ➔ Volcanos/geysers
- Scale height = 80 km
- Not a bound atmosphere - escaping

**Tectonics on Enceladus**

- **Features**
  - Rifts (cracks) 3 km wide in grooved terrain
  - Grooved icy plains geologically younger than cratered region
  - Different colors ➔ different grain size or composition
- **Implications**
  - The world has endogenic processes (liquid inside??)

**Enceladus – Tiger Stripes**

- **Excess heat seen near “tiger stripes”** – crustal rifts

**Geysers on Enceladus**

- Plumes of gas extend 100 km above tiger stripe regions
- Underground pressurized reservoirs of liquid water
- Heated by radioactive decay & tidal flexing

**Enceladus Eruption 2/24/2010**

- **Source:** South polar tiger stripes
- 30 erupting fractures, T ~ 200K
Enceladus Flyby 3/12/08

- North Polar Region
  - 32,000 km altitude, resolution 176m/pix
  - Older region – signs of past warmer sub-surface
- Instruments taking data
  - Neutral and ion mass spectrometer
  - Cosmic Dust Analyzer
  - Compounds are “useful” for life

Enceladus Plume in 3D

Historical Titan

- Discovery
  - Shortly after Galileo discovered Jupiter’s moons
  - Huygens made his own telescope
- Earth observations
  - 1983 – Discovery of CO and N₂ in atm (Owen)
- Voyager
  - Thick atmosphere of N₂, CH₄, C₂H₆, C₂H₂
  - Shrouded in mystery...

Titan Pre-Cassini

- Thick atmosphere
  - N₂ (95%), H₂, C₂H₂, CH₄
  - T_{surf} = 100K – near CH₄ triple point
  - CH₄ → ethane (condenses)
  - CH₄ must have resupply (oceans?)
- Only fully developed atmosphere on a satellite in solar system
- Radar images
  - no oceans

HST image, 10/94

Proposed Titan Meteorology

- Surface conditions
  - Temperature = 94K
  - Pressure = 1.5 bar (Earth = 1 bar)
  - Conditions near triple point for CH₄ can have liquid, solid and gas phase
- Atmospheric chemistry
  - N₂ + CH₄ in atmosphere
  - UV from Sun makes other “organics”: ethane (C₂H₆), acetylene, ...
  - Organics will precipitate!
  - CH₄ must be resupplied.
  - CH₄-ethane rain and lakes?

Jan 2004 – Huygens Probe at Titan

- Stratospheric haze
- Organic particles with H, C, N
- Bottom of layer few 100 km alt, 120 km thick
Descent to a New World: Titan

- During descent, start to see through CH₄ clouds
- High & low albedo regions on surface

Exogenic Processes on Titan

- Only a few craters seen
- Radar image from 1800 km altitude
  - Multi-ringed basin
  - 440 km in diameter

Titan Tectonics

- Mountain ranges
  - Formed from tectonic rifting & upwelling of material
  - Composition: water ice, rock and organic coating
- Top
  - Band of bright clouds – CH₄ fog
  - Caused as wind blows air over mtns and it cools, condensing methane
- Bottom
  - IR image from 12 million km
  - Mtn range 150x30 km
  - 1.5 km height

Rivers on Titan

- Complex network of drainage channels from bright highlands to dark lowlands
- Evidence for Methane springs

An Ancient Sea?

- Hydrocarbons once flowed in this region
- Unknown if this is episodic
- Terrain has no craters → geologically young
Titan Aeolian Features
- Dune fields on Titan
- Hydrocarbons and water ice grains
- Wind speeds during descent
  - 28 m/s at 50 km
  - 10 m/s at 10 km
  - Calmer at surface

Titan Descent 1/14/2005
- 360° view from Huygens during descent
- White areas may be CH₄ (methane) or C₂H₆ (ethane) fog

View from the Surface
- Surface rocks
- Water ice “pebbles”
- Spectrum – red slope unlike anything seen in lab organics

Titan Weather
- North polar cirrus (IR image 2/1/07)
  - Vast clouds of ethane (C₂H₆) and CH₄
  - 30-60 km altitude
- Titan’s seasons – 7 yrs duration
  - N pole currently dark (winter)
  - May be snowing ethane
  - UV breaks up atmospheric CH₄ → C₂H₆ is byproduct
  - Vast oceans were expected – where are they?
  - C₂H₆ dissolves in methane lakes

An Active Hydrological Cycle!
- Discovered 7/22/06 – Radar
  - Dark areas = low reflectivity → smooth, Many lakes 3-70 km
- Morphology
  - Some fill craters
  - Some have rims, origin as seepage
  - Scalloped edges originating from runoff channels
- Suggests active hydrological cycle
  - Methane Rainfall

View from the Surface
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Recent Images of Titan “Hydrology”
- Radar image 12/20/07
- Extensive river systems – Methane rainstorms
- Southern tectonic features

Titan’s Methane Lakes
- Radar image 2/27/07
- 90 km across
- 79 degrees N latitude
- Island ~ big isle HI
- Tan, higher backscatter
- 500 m (smallest features)

Glint from a Titan Lake
- 7/8/2009 - sun glint from Lakes in North

Titan Volcanos
- Volcanic evidence
  - Chemistry in atmosphere suggest volcanic activity
  - Lava is H₂O ice, NH₃ and CH₄
- A Bizarre world – similar to & different from Earth
  - Dirt → organic precipitates
  - Rocks → cold water ice
  - Water → liquid CH₄
  - Magma → water ice and ammonia
- Why Astrobiology cares?
  - Interesting “pre-biotic” chemistry

Life on Titan?