


## Life on Jovian Moons

### LEARNING GOALS

<p><b>9.1 THE MOONS OF THE OUTER SOLAR SYSTEM</b></p> <ul style="list-style-type: none"> <li>What are the general characteristics of the jovian moons?</li> <li>Why do we think that some moons could harbor life?</li> </ul>	<p><b>9.2 LIFE ON JUPITER'S GALILEAN MOONS</b></p> <ul style="list-style-type: none"> <li>Does Europa have an ocean?</li> <li>Could Europa have life?</li> <li>Could other moons of Jupiter have life?</li> </ul>	<p><b>9.3 LIFE AROUND SATURN, AND BEYOND</b></p> <ul style="list-style-type: none"> <li>Could Titan have life?</li> <li>Could other moons of Saturn have life?</li> <li>Could moons of Uranus or Neptune have life?</li> </ul>	<p> <b>THE PROCESS OF SCIENCE IN ACTION</b></p> <p><b>9.4 CHEMICAL ENERGY FOR LIFE</b></p> <ul style="list-style-type: none"> <li>What is the role of disequilibrium in life?</li> <li>What types of chemical reactions supply energy for life?</li> </ul>
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## Jovian Moons

### Comparison of Orbits and Sizes

#### Jovian Planets:

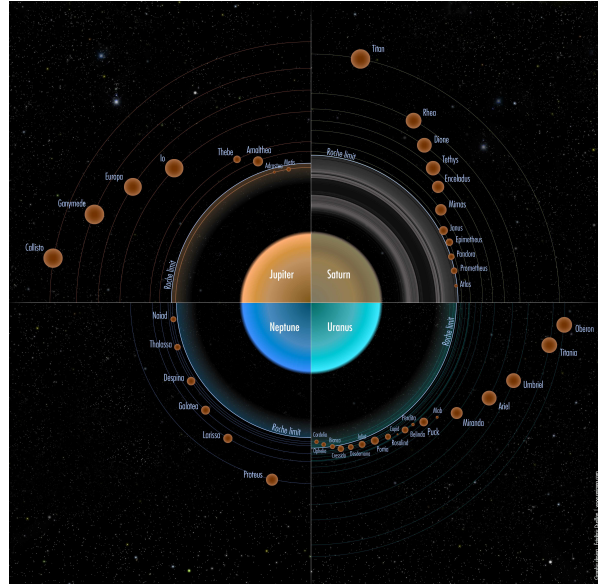
- Jupiter 5 AU
- Saturn 10 AU
- Uranus 20 AU
- Neptune 40 AU

#### In this image:

Planet radius normalized so that orbit of moons on comparable scale

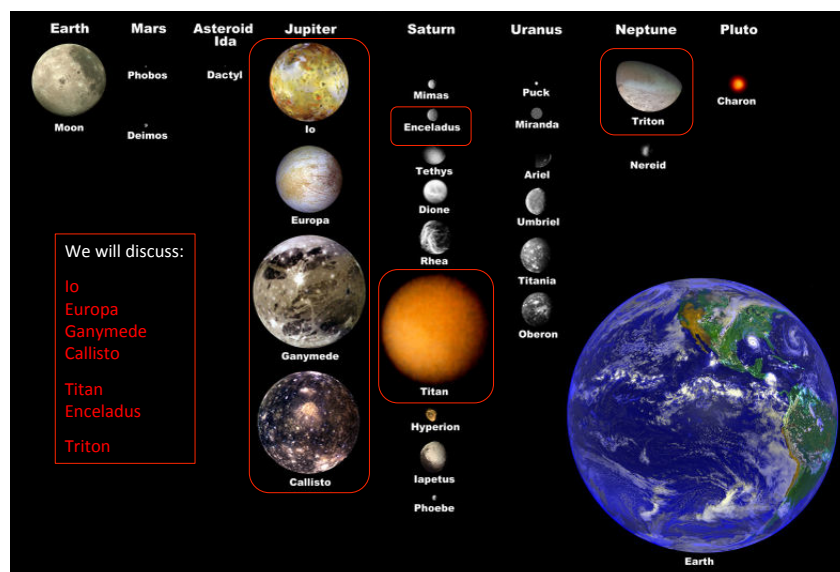
#### Roche Limit:

Distance from planet inside of which moons cannot exist- tidal forces from planet tear moons apart; rings found inside Roche limit



## Jovian Moons

### Comparison of Sizes and Surfaces





## Habitability of Jovian Moons?

The moons must meet the three conditions for Habitability: Elements, Energy, Water

First, let's consider **energy for life**

Far from the sun solar energy is relatively low.  
Need another source of energy -> **tidal forces**

Tidal forces derive from the inverse square law of gravity. The near side of a planet or moon feels a stronger force than the far side. This is called a **differential force** and it stretches a planet/moon. If the tidal force varies with time, this stretching changes with time and this heats the planet/moon through internal friction

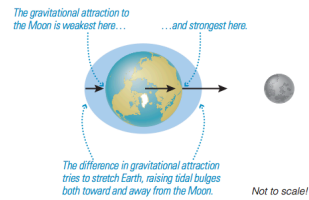


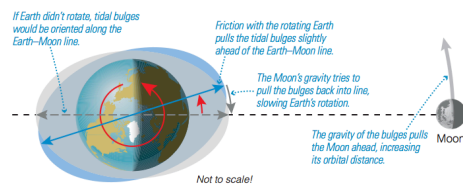
Figure 9.7

Tides on Earth are created by the varying force of attraction between different parts of Earth and the Moon. There are two daily high tides as any location on Earth rotates through the two tidal bulges. The diagram highly exaggerates the tidal bulges, which actually raise the oceans only about 2 meters and the land only about a centimeter.

This tidal (frictional) heating is an energy source. In addition, **tidal heating slows the rotation of a planet/moon**. To compensate, **the moon's orbit slowly moves outward with time (conservation of angular momentum)**.

Figure 9.8

Earth's rotation pulls its tidal bulges slightly ahead of the Earth-Moon line, leading to gravitational effects that very gradually slow Earth's rotation and increase the Moon's orbital distance.



## Habitability of Jovian Moons?

### Tidal Heating Slows Rotation of Moon

The rotation of a moon on its axis can be slowed until the moon is locked into always showing one face to the central planet, this final state is called **synchronous rotation**



a If you do not rotate while walking around the ball representing Earth, you will not always face it.



b You will face Earth at all times only if you rotate exactly once during each orbit.

Nearly all Jovian Moons exhibit **synchronous rotation**; they have the same face toward the main planet during their orbits.

The Earth's moon is synchronous (we only see one face of it).

This locked-in type of orbit is common and is result of **tidal forces** having been applied for a long period of time (a few billions of years).

## Habitability of Jovian Moons?

### Tidal Heating of Moons

For tidal heating to provide energy input into a Jovian moon, the tidal forces must change with time or the frictional effect cannot operate. But, the moons are synchronous, so the friction cannot come from the rotation of the moon! So, how does tidal heating work for the Galilean satellites?

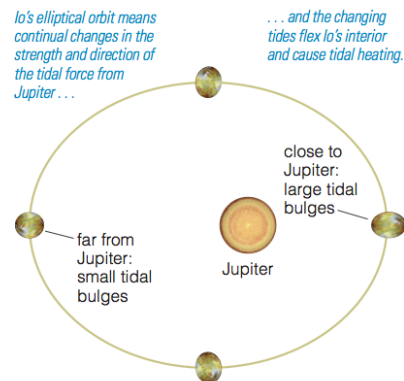
**EXAMPLE:** Consider Io.  
It has a highly elliptical orbit.

When Io is at its **closest approach** to Jupiter, it feels the **strongest tidal forces**.

When Io is at its **farthest position** from Jupiter, it feels the **weakest tidal forces**.

**Because of its highly elliptical orbit, the tidal forces on Io change with time, cycling from strongest to weakest during each orbit of Io.**

Thus, Io is continually being heated by internal friction from tidal forces from Jupiter. Same applies to Europa, Ganymede, and Callisto.



## Habitability of Jovian Moons?

### Orbital Resonance

There remains a problem for these moons

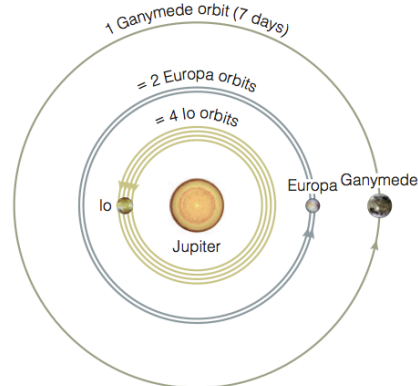
For life to persist on these moons, the energy input must be stable for 100s of millions, if not a few billions, of years.

But tidal friction causes moon orbits to increase- they move further away from the central planet with time.

As a moon moves further away, the strength of the tidal heating decreases, so with time the energy input into these moons would become negligible, the moons would cool as they move further away, and the energy for life would come to an end.

How can this be resolved?

**Orbital Resonance between the moons**

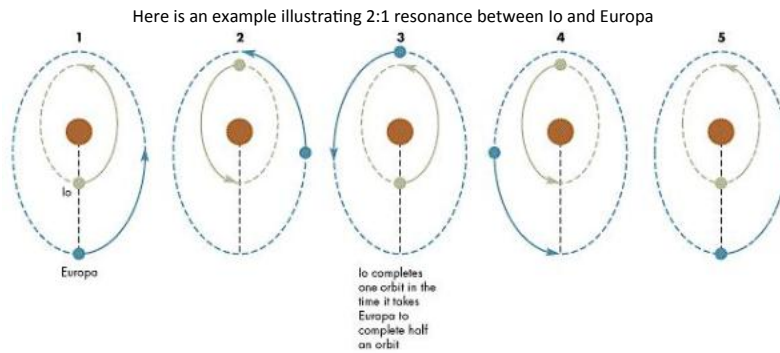


The gravitational interplay between Jupiter's moons has locked their orbits such that the inner three align every 7 Earth days.

*In systems with multiple moons, the moons interact gravitationally with one another until a steady-state orbital configuration is finally achieved. The resonance results in the orbits being fixed with time. Thus, the moons do not move further away and the energy input from tidal forces is stabilized for billions of years. Problem solved.*

## Habitability of Jovian Moons?

### Orbital Resonance



With time, the gravitational pulls of the two moons set up a steady-state orbital configuration; in the case of Io and Europa, the equilibrium configuration is a 2:1 resonance: for every two orbits of Io, Europa orbits one time. Once resonance sets in, the orbital periods and the sizes of the orbits remain fixed.

<http://youtu.be/tJXZ05Hphqg> VIDEO: resonant orbits (silent) 0:48

## Jupiter

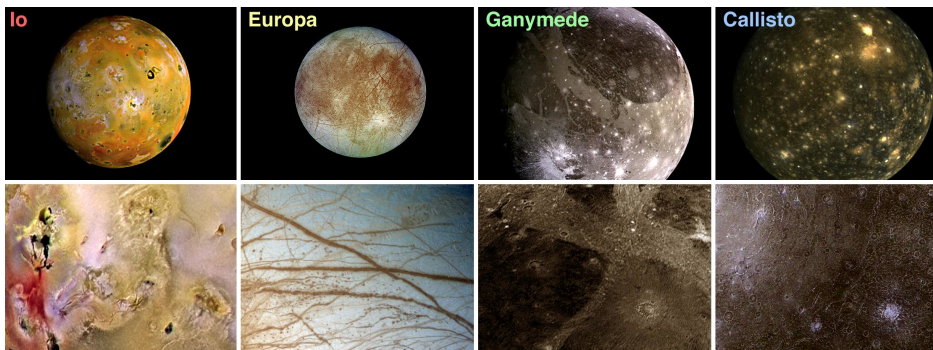
### The Galilean Satellites

In 1620, Galileo discovered four “stars” that moved in proximity to Jupiter. Due to their regular periodic return to their locations, he soon realized that they orbited Jupiter. He discovered the first moons around another planet.

Galileo's hand written observations from 1620 are shown to the right. They were just points of light to him; but today, 400 years later, you and I see these as real dynamic worlds.

*Observations of Jupiter*  
1620

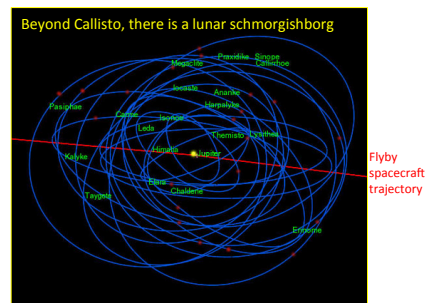
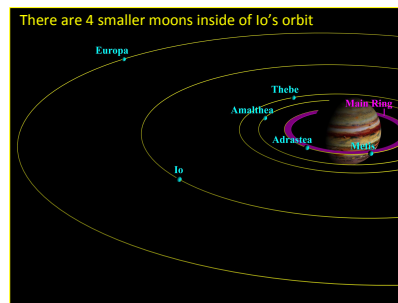
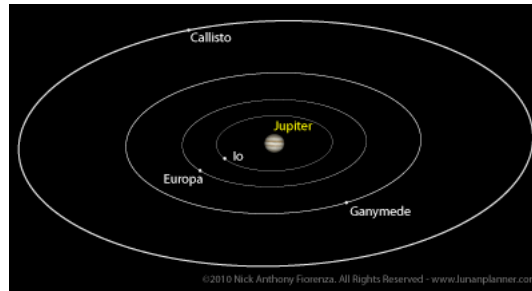
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2. Jovis		○ * * *
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3. H. 12		* ○ *
4. mare		* ○ * *
6. mare		* * ○ *
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10. mare		* * * ○ *
11.		* * * ○ *
12. H. 12		* ○ *
12. mare		* * * ○ *



## Jupiter

### The Galilean Satellites

- Io
- Europa
- Ganymede
- Callisto



<http://youtu.be/5l2tR2smeHY> VIDEO: Jupiter's Moons (silent) 0:33

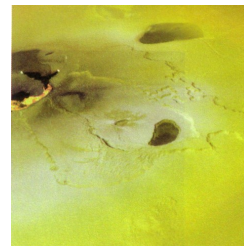
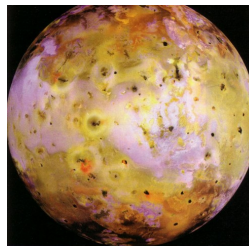
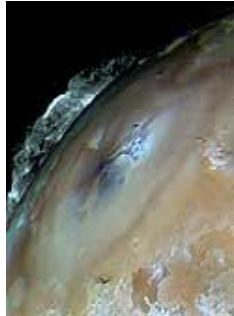
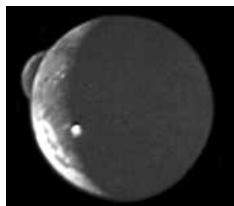
## Io

Habitability Probability: Low?

Two conditions met: chemicals and energy for life, but water not present. (extremophiles?)

<http://youtu.be/GkfDnlQsEXs> VIDEO: Io volcanoes and tidal heating 2:20

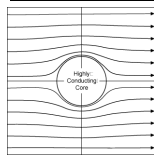
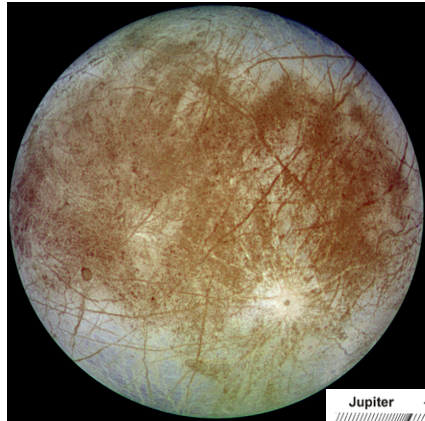
[https://www.youtube.com/watch?v=RTGbXN4qm\\_I&spfreload=10](https://www.youtube.com/watch?v=RTGbXN4qm_I&spfreload=10) VIDEO: alternative theory – not volcanoes, but electric arcs 10:21



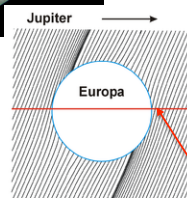
(left) Black, brown, and red spots are recent volcanic features. White and yellow regions are sulfur and sulfur dioxide deposited on the moon from the eruptions. (right) Note the extremely hot lava...

(upper) Voyager discovery image from 1979 showing a volcanic plume on Io  
(lower) Galileo image from 1995 of the same plume.

## Europa



External magnetic field lines bend in the presence of a electric conductor



Tidal forces on Europa are about 1000 times stronger than the moons effect on the Earth.

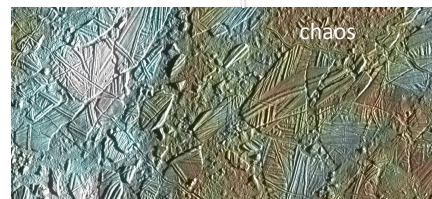
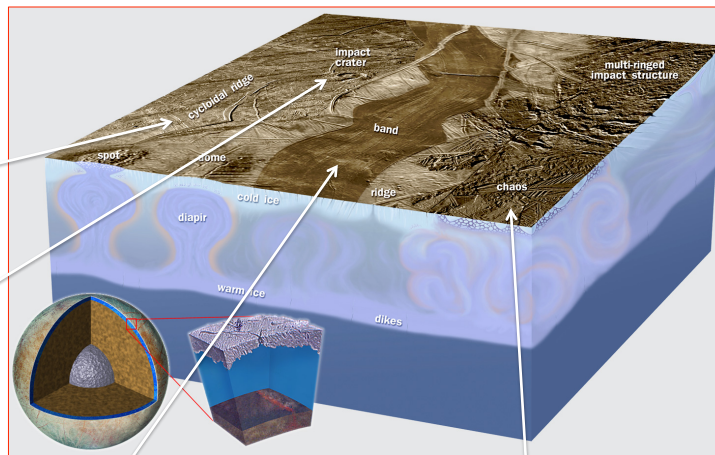
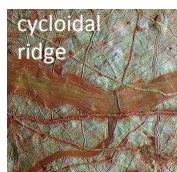
### Strong evidence for an ocean

1. Small number of craters means a young surface
2. Chaotic and flooded terrain well explained by icy skin on top of ocean
3. Magnetic field currents due to interaction with Jupiter's magnetic field shows that something conducts electricity beneath the surface- a briny ocean?
4. Calculations indicate tidal heating from Jupiter is sufficient to keep most or Europa's ice melted

Europa exhibits electrical currents on or below its surface that bend Jupiter's magnetic field lines ever so slightly. → liquid motions

Path of Galileo spacecraft

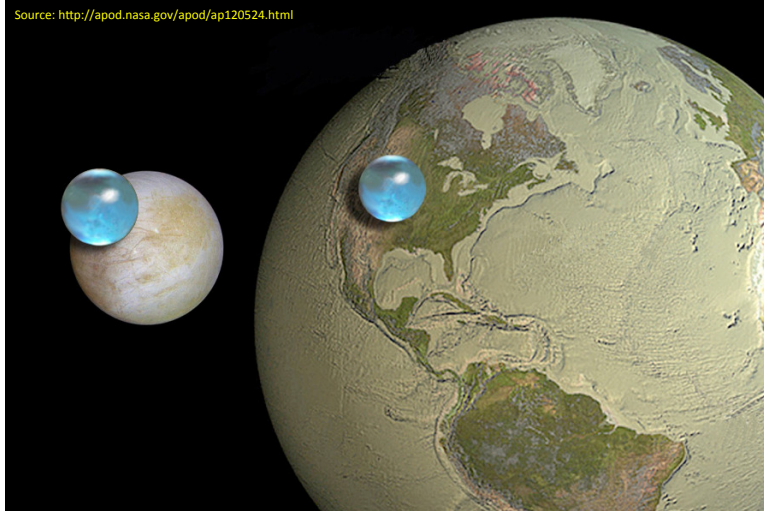
## Europa





**How much of Jupiter's moon Europa is made of water?** A lot, actually. Based on the Galileo probe data acquired during its exploration of the Jovian system from 1995 to 2003, Europa possesses a deep, global ocean of liquid water beneath a layer of surface ice. The subsurface ocean plus ice layer could range from 80 to 170 kilometers in average depth. Adopting an estimate of 100 kilometers depth, if all the water on Europa were gathered into a ball it would have a radius of 877 kilometers. To scale, this intriguing illustration compares that hypothetical ball of all the water on Europa to the size of Europa itself (left) - and similarly to all the water on planet Earth. With a volume 2-3 times the volume of water in Earth's oceans, the global ocean on Europa provides tantalizing destination in the search for extraterrestrial life in our solar system.

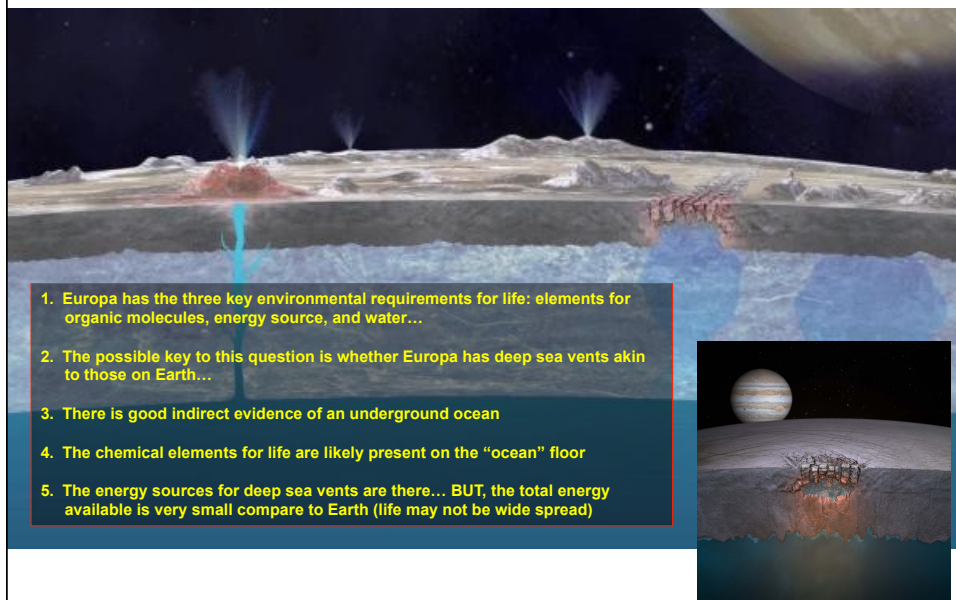
Source: <http://apod.nasa.gov/apod/ap120524.html>



## Europa

Habitability Probability: Very High

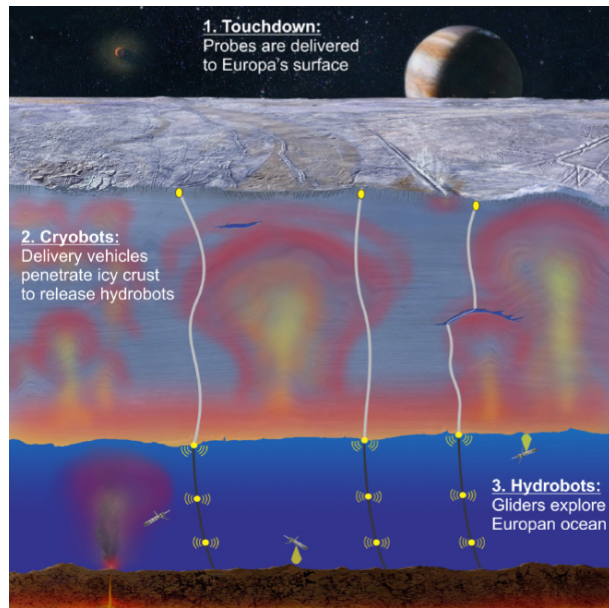
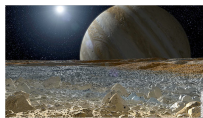
Europa is the most favored location on which to search for life in our solar system.



## Europa

Worthy of Exploration!

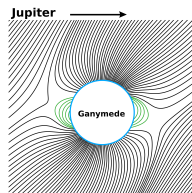
Send probes!!!

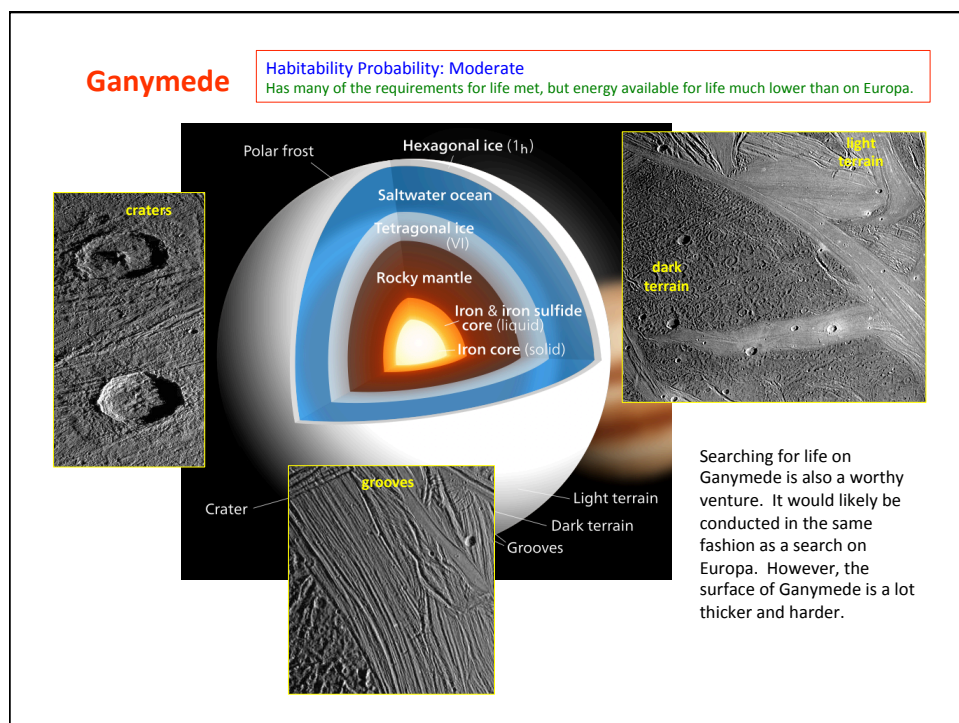
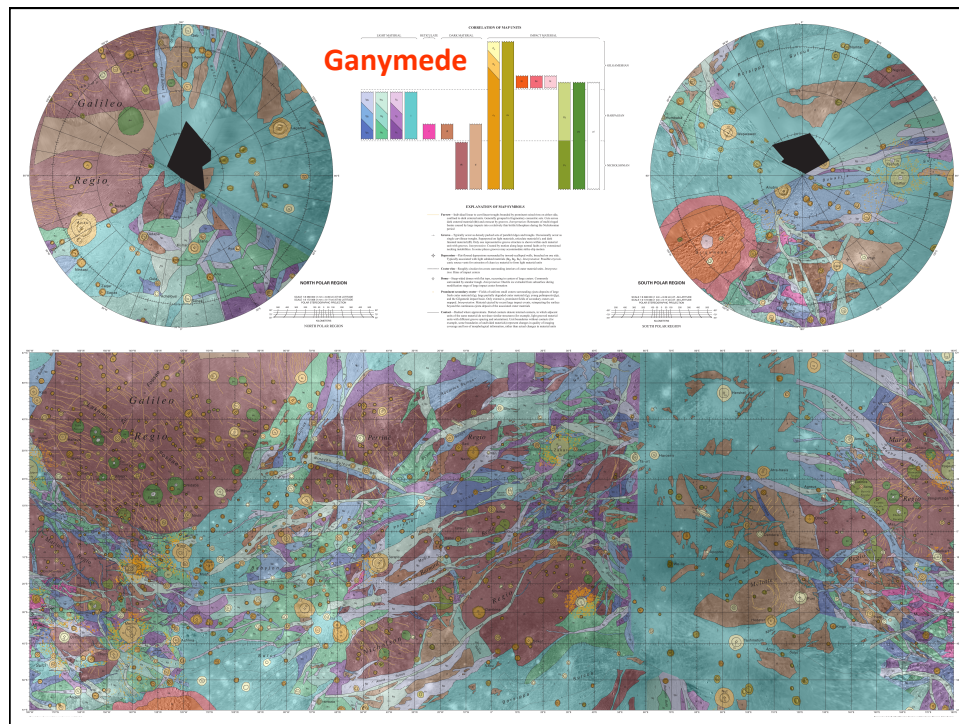


## Ganymede

- Both young and old surfaces; dark areas covered with craters (old) and lighter areas look "repaved" and have "grooves"
- Younger areas may have resulted from "water eruptions"
- Has a magnetic field, suggestive of a salty subsurface ocean or molten convective core?
- Young areas show presence of salts!
- Larger than Europa, so could retain internal heat better
- Ice layer may be 150 km thick
- **If there is life**, it would probably be very simple, like the pre-cells of early Earth, and it would be localized very deep in the putative ocean

Ganymede's weak magnetic field (green). Note how Jupiter's field is affected.

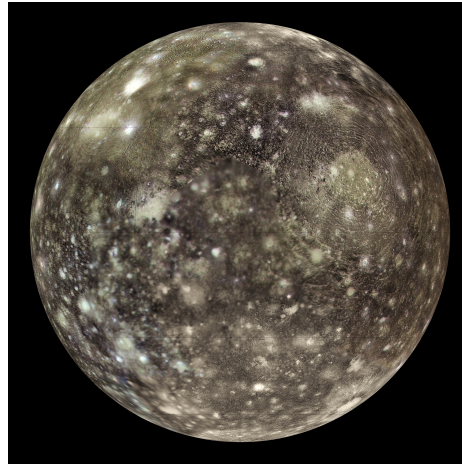
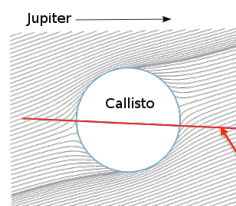






## Callisto

- Entire surface marked by heavy bombardment; old surface
- Likely undifferentiated mixture of ice and rock, perhaps with 100 km of water ice below the crust
- Lack of differentiation implies little internal heat source (Callisto farthest from Jupiter of Galilean moons and does not yet partake in orbital the resonances with other moons)
- Has an "induced" magnetic field (salty ocean?)

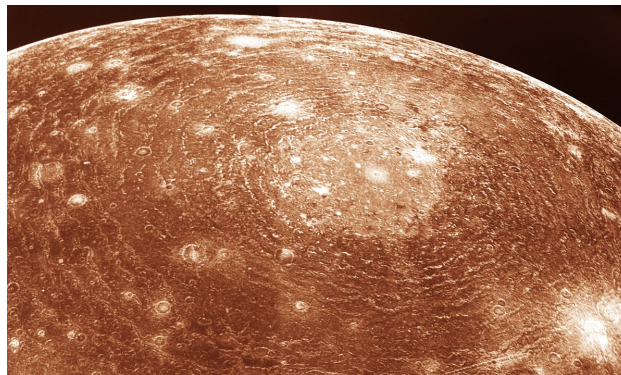


Like Ganymede, Callisto exhibits electrical currents on or below its surface that bend Jupiter's magnetic field lines ever so slightly.

- liquid motions
- underground liquid ocean

Path of Galileo spacecraft

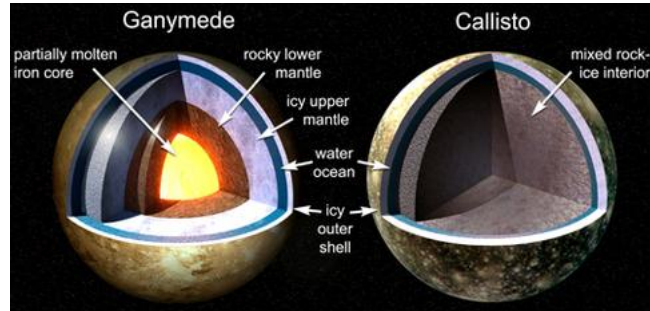
## Callisto



The second piece of evidence for a deep unseen ocean is the Valhalla crater.

Unlike with a similar sized crater on Mercury, there is no bulge on other side of Callisto (meaning that the shock of the impact was absorbed); an underground fluid (ocean) would serve as an excellent shock absorber.

### Ganymede and Callisto Internal Structures (models)

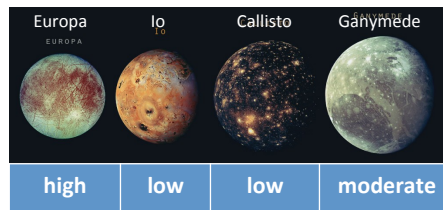


### Callisto

Habitability Probability: Low

The first two requirements for life met, but energy is so low that life probably not sustainable.

Galilean Moon  
Habitability  
Probability  
Scorecard



### Saturn The Saturnian Satellites

62 moons and counting

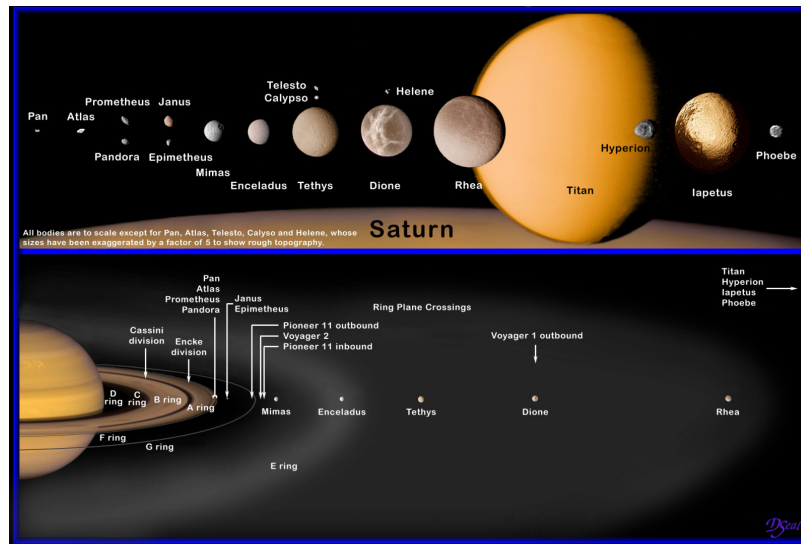
Focus:

- Titan
- Enceladus



## Saturn

### The Saturnian Satellites



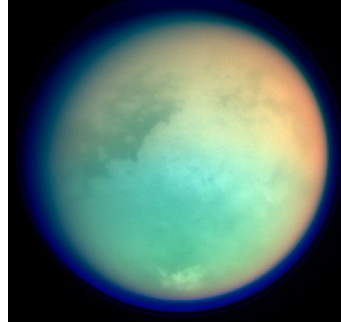
## Titan

- 2<sup>nd</sup> largest moon in solar system
- has a substantial atmosphere, even thicker than Earth's
- **liquid methane lakes on its surface!** (only other solar system object with open bodies of fluid on its surface)
- atmosphere is essentially a smog cloud  
90% molecular nitrogen, 6% methane and ethane, trace propane (oil companies stay away!)
- Atmospheric pressure close to Earth's, but temperature is chilly -180 C (-290 F). This is bad for metabolism rates!
- Believed to have undifferentiated(?) silicate core, a mantle of compressed ices, and an underground liquid water ocean

visible light- sunlight reflected off clouds

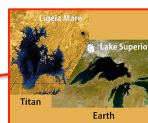
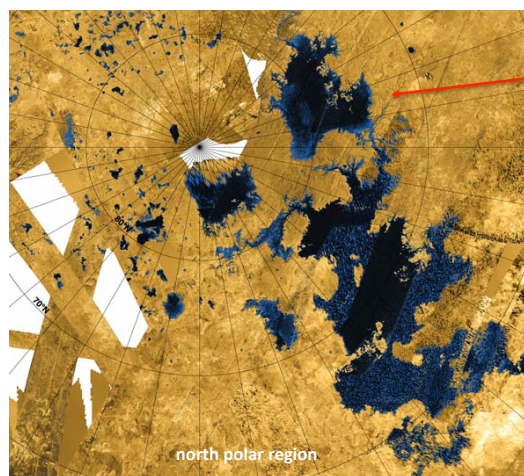


infrared light- emission from clouds+surface



## Titan

**Methane lakes.** A lot of methane lakes Titan's surface is mostly methane ice, water ice, and likely some ammonia ice. A real nasty hydrocarbon stink.



Some lakes much larger than the Great Lakes in the USA!



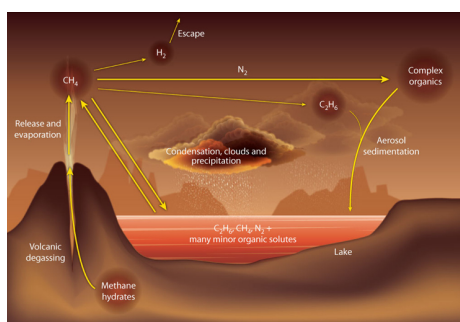
Rocks are water ice!



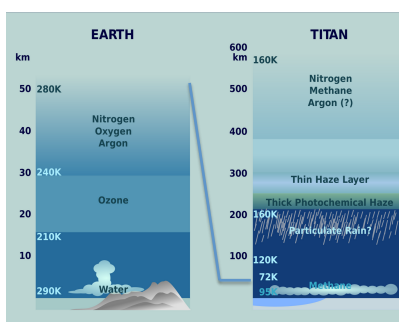
<https://www.youtube.com/watch?v=YJVvAt5U2KE&spfreload=10> VIDEO: Welcome to Titan 3:02

## Titan

**Atmosphere.** Titan's atmosphere is more than 10x higher than Earth's atmosphere!  
The methane cycle on Titan is believed to involve methane spewing volcanoes.



Methane injected into Titan's atmosphere via volcanoes, some hydrogen dissociates from the methane and escapes to space. The dissociated methane can self react to form ethane and can also react with nitrogen to form the thick photochemical smog layer. Some of the ethane and complex organic molecules precipitate as rain and sustain lakes of methane, ethane, and nitrogen infused organic molecules. [bases upon a 2014 *Nature* paper]



Earth's atmosphere extends to about 50 km.  
Titan's atmosphere extends to about 600 km.

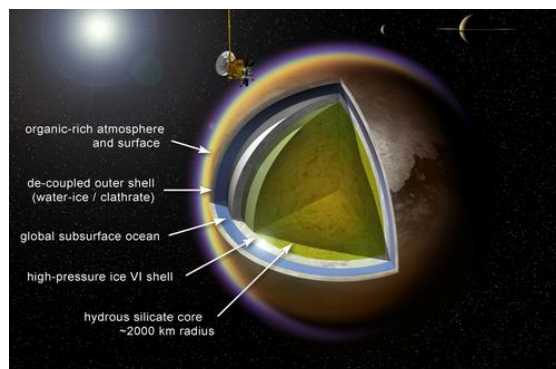
Earth clouds (water vapor) are at 290K (60F) below 10 km.  
Titan clouds (methane) are 95K (-285F) below 25 km.

## Titan

Habitability Probability: Questionable

Has the elements/chemistry/water for life, but temperature and energy available for life very low.

**Structure.** The **core** is undifferentiated silicates. The **mantle** is ice, with a liquid water ocean. The **surface** is methane ice, water ice, and ammonia ice (a nitrogen based hydrocarbon). The **atmosphere** is rich with organic molecules.



Life as we know it probably cannot exist in the organic-rich surface lakes. There is no liquid water in these lakes; they are below the freezing point of water. If there is life, it would probably be in the underground liquid water ocean. But to our present knowledge, the energy budget (and temperature) in this ocean is too low to support life.

## Titan

### Underground liquid Ocean; how can that be?

The temperatures on the surface of Titan are -285 F (-180 C), so water forms ice rocks!

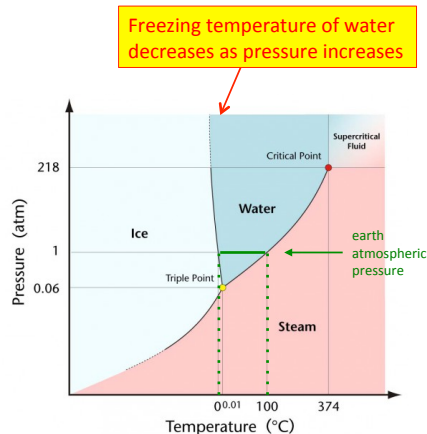
But below the surface the temperature increases somewhat, this helps a little

It's the increase in pressure as you go below the surface that makes liquid water possible below the surface.

Water under pressure can stay in liquid form well below its "normal" Earth freezing temperature. A high pressure environment may not be conducive to life.

<http://www.space.com/16348-titan-ocean-saturn-moon.html>  
ARTICLE: Titan's Underground Ocean

<http://www.centauro-dreams.org/?p=1784>  
ARTICLE: Musings on Titan's Sub-Surface Ocean



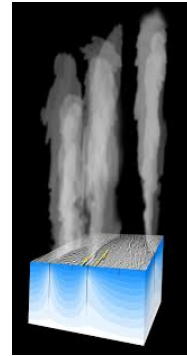
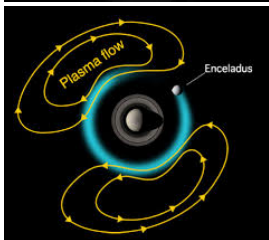
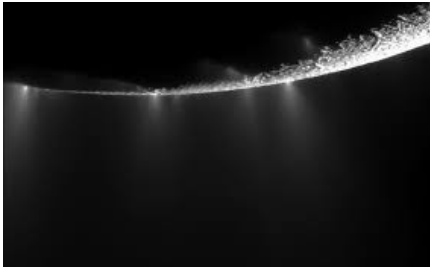
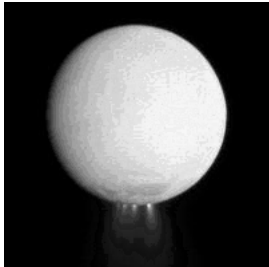
On Earth, the temperature range of liquid water is 0-100 Celsius. On planets with lower pressure, the range is narrower. In environments where the pressure is higher, the range is broader.



## Enceladus

### Water Geysers

<https://www.youtube.com/watch?v=hOCTKrAU05s&spfreload=10> VIDEO: Enceladus 2:22



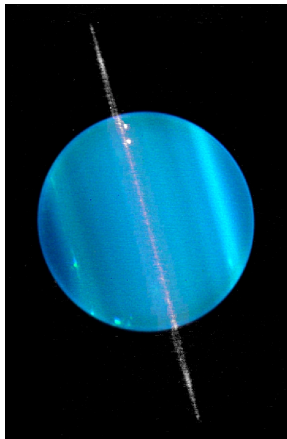
Artistic impression of interior of moon

Until this discovery, the origin and persistence of the E ring was a mystery. We now know that the E ring is created by the stripping of the water from Enceladus.

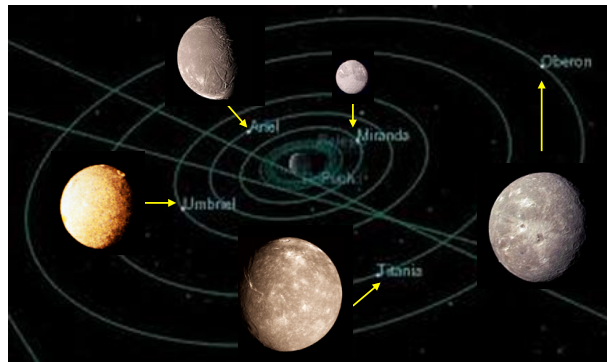
## Uranus

### Uranian Satellites

Uranian moons are divided into three groups:  
13 inner moons  
5 major moons  
9 irregular moons



### 27 moons and counting



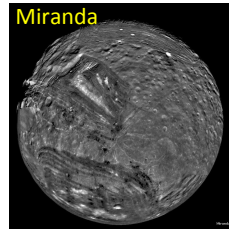
The 5 major moons of Uranus (relative sizes to scale)

One mission to Uranus. The flyby of *Voyager 2* in 1989. It snapped as many photos as it could, made some spectroscopic measurements, and sniffed for magnetic fields... but it never really got close enough to any of the moons to obtain details that even compare to what *Cassini* obtained around Saturn.

## Uranus

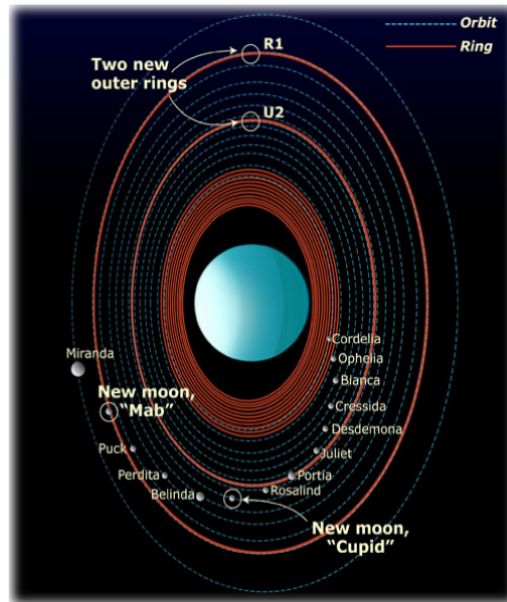
### Uranian Satellites

The *Hubble Space Telescope* recently discovered two new moons and two new rings.



Miranda is an ugly mess! It was originally thought that it suffered a "face lifting" collision, but the latest thinking is that it is geologically active due to tidal heating.

We have a great deal left to learn about the Uranian system.



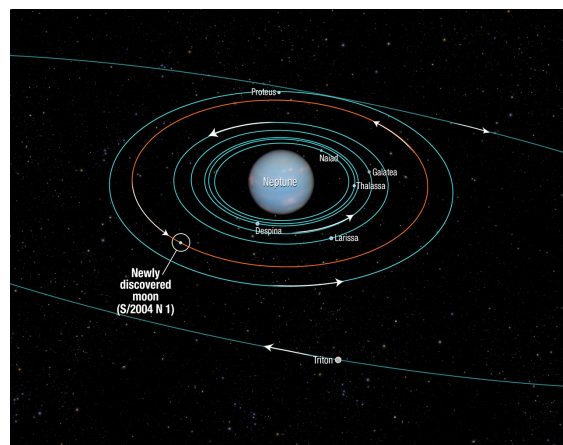
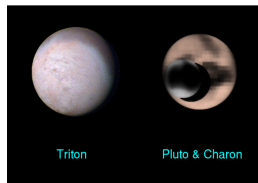
## Neptune

### Triton

Triton is a captured **Kuiper Belt** object; it has a highly elliptical retrograde orbit

The "dwarf planet" Pluto is also a **Kuiper Belt** object.

Triton is roughly the same size as Pluto!

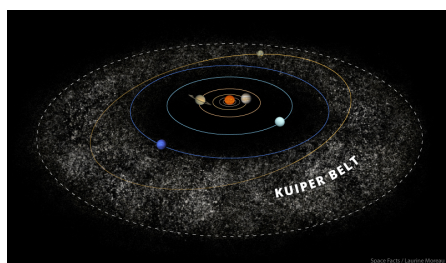
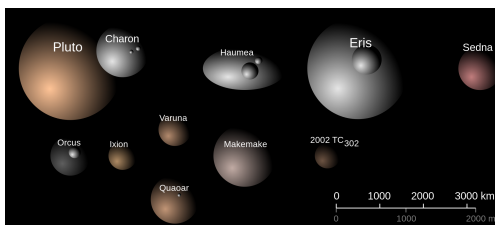


What is the Kuiper Belt?

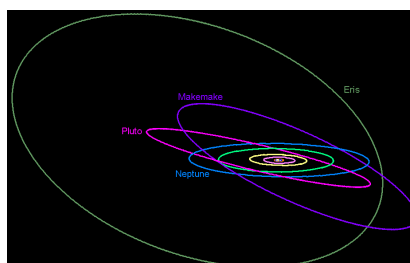
## Kuiper Belt Dwarf Planets

Since 2005, we have been discovering new Pluto-like objects in the outer reaches of the solar system. Turns out there is a huge reservoir of rocky/icy material beyond the orbit of Neptune.

<https://www.youtube.com/watch?v=XXoZwERokml&spfreload=10>  
VIDEO: Kuiper Belt (2:46)



Discovered 60 years after Pluto, the **Kuiper Belt** is a vast "3<sup>rd</sup> component" of the solar system; it is the remains of the solar system's formation; it contains billions of small rocky objects and countless dwarf planets.



Orbits of the dwarf planets Pluto, Eris, and Makemake.

These worlds may have geysers, water, and are very bit as intriguing as, say, the moons of Jupiter and Saturn.

## Neptune Triton

- retrograde orbit, probably did not form in Neptune system, but was captured late
- Few impact craters, surface young and varied
- only likely internal heat source for resurfacing (repaving) is radioactive decay
- Water, methane geysers erupt (methane serves as anti-freeze for water!)
- Has a thin atmosphere with winds
- surface is cold (-230C), but internal region may have some warmth for life to exist, but this is unlikely

