

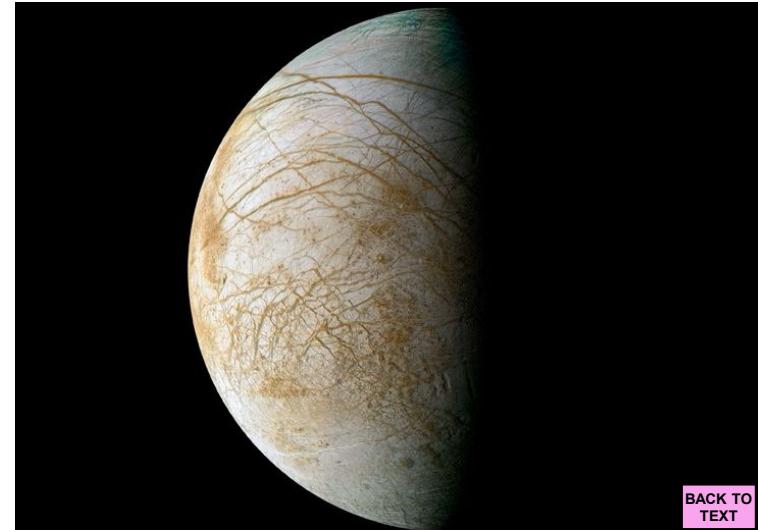
# Lecture 9: Life Elsewhere in the Solar System?

## Aims of Lecture

- (1) To discuss the possibilities for life elsewhere in the solar System
- (2) Briefly to discuss the possibility that life might transferred between planets in meteorites

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Fig. 1. Galileo spacecraft image of Europa. (NASA).

## 1. Introduction

Although Mars is widely considered to be the most likely place to find evidence for past or present life elsewhere in the Solar System there are other interesting possibilities. Foremost among these are the water-rich moons of the outer Solar System, especially Jupiter's moon Europa (Fig. 1) and Saturn's moon Enceladus, which are thought to have oceans of liquid water below icy crusts. Titan, the largest moon of Saturn, is also an interesting possibility given its thick atmosphere rich in organic molecules. Conceivably, the atmospheres of the giant planets, and perhaps even Venus, might provide habitable environments.

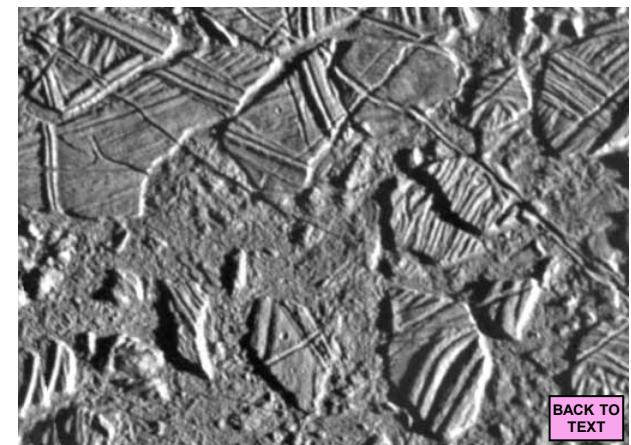
## 2. Europa

With a radius of 1565 km, Europa is the smallest of Jupiter's Galilean satellites, being slightly smaller than the Moon. Although it has an icy surface (Fig. 1), its average density of 3.0 g/cm<sup>3</sup> implies that it must be mostly made of rock, with an outermost water-rich layer being at most 100 to 200 km thick.

### 2.1 Evidence for an ocean

There are several lines of evidence which suggest a sub-surface ocean within Europa:

- The paucity of impact craters (Fig 1) implies efficient resurfacing, and a surface age of only 10 to 100 million years. This is in particular contrast to the heavily cratered icy surfaces of Ganymede and Callisto. A sub-surface source of liquid water, which if erupted onto the surface, would obliterate pre-existing craters, is a plausible explanation.
- Tidal heating of the interior of Europa by Jupiter's gravity means that there is a source of energy available to keep an ocean liquid over the age of the solar system.
- Images of the surface obtained by Galileo reveal some areas which resemble ice floes on Earth (Fig. 2), and which suggest the 'rafting' and cracking of ice blocks over a liquid substrate.
- Infrared spectra of dark patches on the surface (Fig. 1) obtained by Galileo have been interpreted as being due to hydrated salts (such as epsomite,  $MgSO_4 \cdot 7H_2O$ ), which may have been deposited by the evaporation of brines derived from an underlying salty ocean.

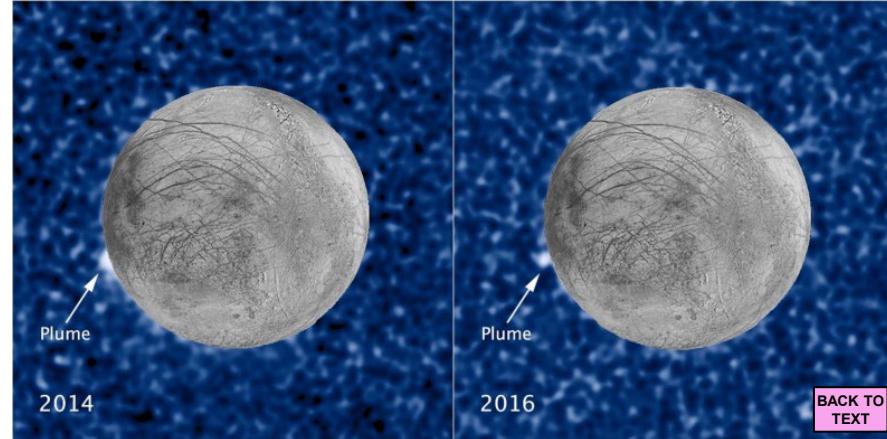


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**Fig. 2.** High-resolution Galileo image of 'chaotic terrain' on Europa which resembles areas of sea ice on Earth. The image is ~30 km wide, and the resolution is 54 meters per pixel (NASA).

- Although Europa seems not to have a magnetic field of its own, the Galileo magnetometer experiment found that it distorts Jupiter's magnetic field in a manner which suggests the presence of a sub-surface electrical conductor. This is consistent with the presence of a salty ocean.
- Models of surface crack formation by tidal flexing indicate that Europa's crust is decoupled from the underlying mantle, consistent with an ocean between them.
- In 2014 and 2016 the HST observed possible plumes of water or vapour escaping from a region on Europa (Fig. 3), similar to those observed on Saturn's moon Enceladus (see Section 4 below). Independent support for these plumes came in 2018 when an analysis of Galileo magnetometer data from a 1997 fly-by of Europa identified a magnetic signature similar to those found in the Enceladus plumes by Cassini.

Definitive proof of a sub-surface ocean will require additional space missions, and in particular a Europa orbiter. Key measurements would include a laser altimeter to accurately measure the tidal deformation of the surface as it orbits Jupiter (the manner of which will depend on the thickness of the crust) and/or a ground-penetrating radar which should be able to detect an ice-water interface if this is present. Ultimately, it would be desirable to land seismometers on the surface, but this will be a much more difficult undertaking.



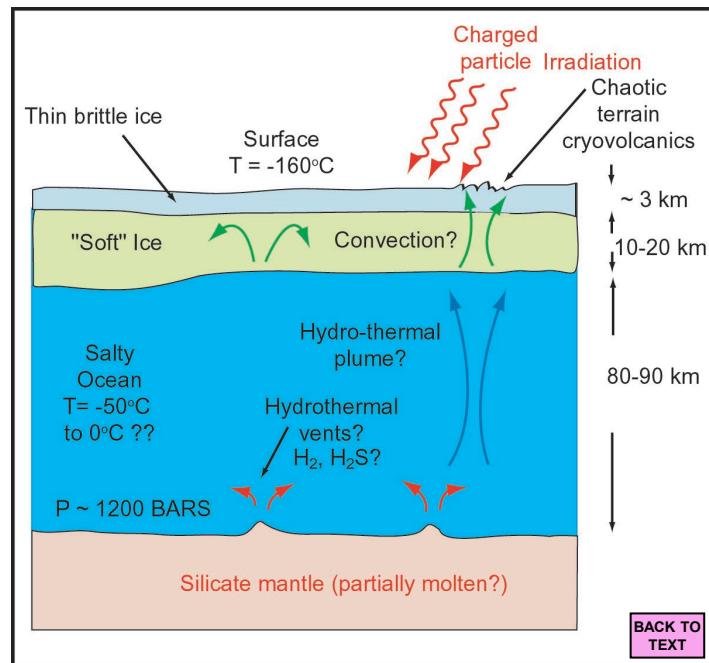
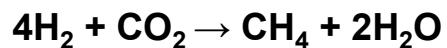
**Fig. 3.** Composite images by NASA's Hubble Space Telescope and Galileo spacecraft, show a suspected plume of material erupting two years apart from the same location on Europa (NASA).

## 2.2 Habitability of a Europan ocean

Fig. 4 shows a schematic illustration of a hypothetical Europan ocean. The surface ice is continually bombarded with radiation from space, and we will see that this may be an important energy source for any organisms which may exist below the surface. Hydrothermal vents may provide another source of energy at the bottom of an ocean – their presence is purely hypothetical, but tidal heating of the silicate mantle by Jupiter's gravity means that they are possible in principle.

Given an ocean, one of the three main prerequisites for life is present (Lecture 7). Thus, in order to assess the habitability of a Europan ocean we must address the availability of the other two – energy and a source of organics.

There will be no light in a Europan ocean, so photosynthesis will not be possible. It follows that any life-forms which may be present must be either chemoautotrophs or, given a source of organic molecules, chemoheterotrophs. It is important to remember that most deep-sea chemosynthesis on Earth relies on dissolved O<sub>2</sub>, which has ultimately been produced at the surface by photosynthesis. Clearly this would not be an option on Europa. On the other hand, as we saw in Lecture 7, chemosynthesis using hydrogen as an electron donor, and CO<sub>2</sub> as an electron acceptor and carbon source, would still be possible using reactions such as:



**Fig. 4.** Schematic illustration of the possible structure of a Europan ocean; see text for details.

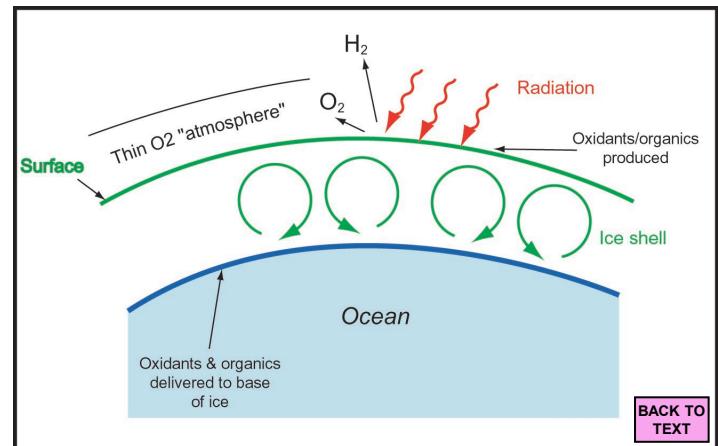
If hydrothermal vents are present on the ocean floor (Fig. 4), serpentinization reactions may lead to the outgassing of H<sub>2</sub>. CO<sub>2</sub> has been detected on the surface spectroscopically (where it occurs at a concentration of ~0.2%) and may therefore be present in the ocean. Thus the use of redox energy to drive chemosynthesis is possible in principle. In addition, as discussed in Lecture 5, hydrothermal vents might also synthesise organic compounds which could then be utilised by heterotrophs.

While hydrothermal vents, if they exist, will be located at the bottom of the ocean, the upper levels immediately below the icy shell, may also be provided by a source of organics and chemical energy. Intense radiation at the surface can produce oxygen by the dissociation of water molecules in the ice. The light hydrogen escapes to space, but the heavier oxygen is trapped in a thin ‘atmosphere’ (with a surface pressure of ~10<sup>-11</sup> bar; Fig. 5).

Some of this oxygen, and related oxidants (e.g. OH and H<sub>2</sub>O<sub>2</sub>) may get trapped in the surface ice. Moreover, irradiation of the icy surface may also produce organic molecules through Urey-Miller type reactions. Once trapped in the surface ice, convective overturn (Fig. 5) within the ice, and/or occasional melting from below (Fig. 6), could transport these oxidants and organics to the ocean below (Fig. 5). Once there, the oxidants would be available for chemosynthetic redox reactions, e.g.:



In addition, any organic molecules delivered to the ocean from above would potentially be available for heterotrophs.



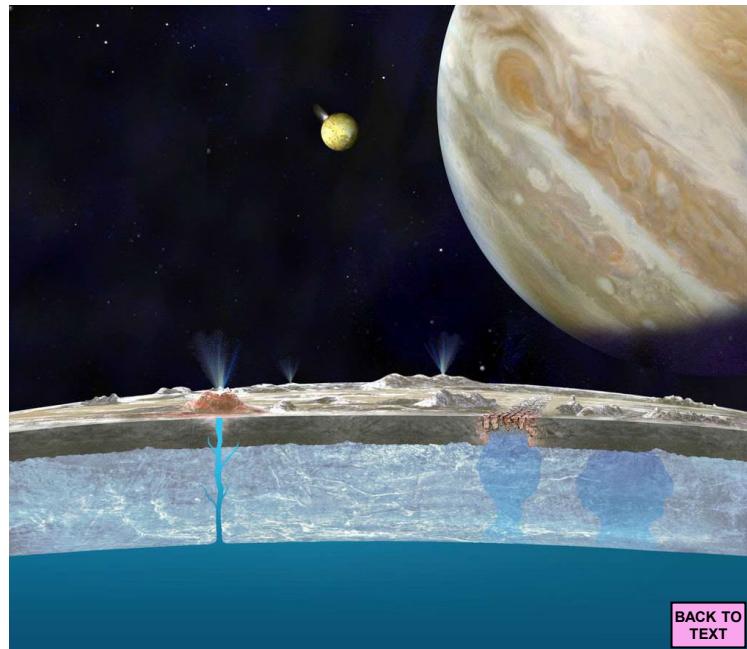
**Fig. 5.** Convective overturn in Europa’s icy crust could in principle transport oxidants and organics to a subsurface ocean. The extent to which this actually occurs is presently unknown.

## 2.3 Searching for life on Europa

Unfortunately, searching for life in a Europan ocean will not be easy! It is conceivable that interactions between the ocean and the surface (e.g. convecting ice or upwelling water) could carry biosignatures (e.g. complex molecules, or even whole organisms) to the surface where they might be sampled robotically. If predictable outgassing plumes can be identified then such sampling might be done from orbit.

If the ice shell is sufficiently thin, at least in localised areas (Fig. 6), it might be possible to land a spacecraft and drill through it to sample the ocean directly (Fig. 7). However landing on Europa will be very difficult, not least because of Jupiter's gravity and radiation environment, and such missions undoubtedly lie decades in the future.

**Fig. 7.** One (rather ambitious!) scheme for a probe to explore (hypothetical) hydrothermal vents on the floor of Europa's sub-surface ocean (NASA).



**Fig. 6.** NASA graphic showing the possible sub-surface structure of Europa (JPL/NASA).



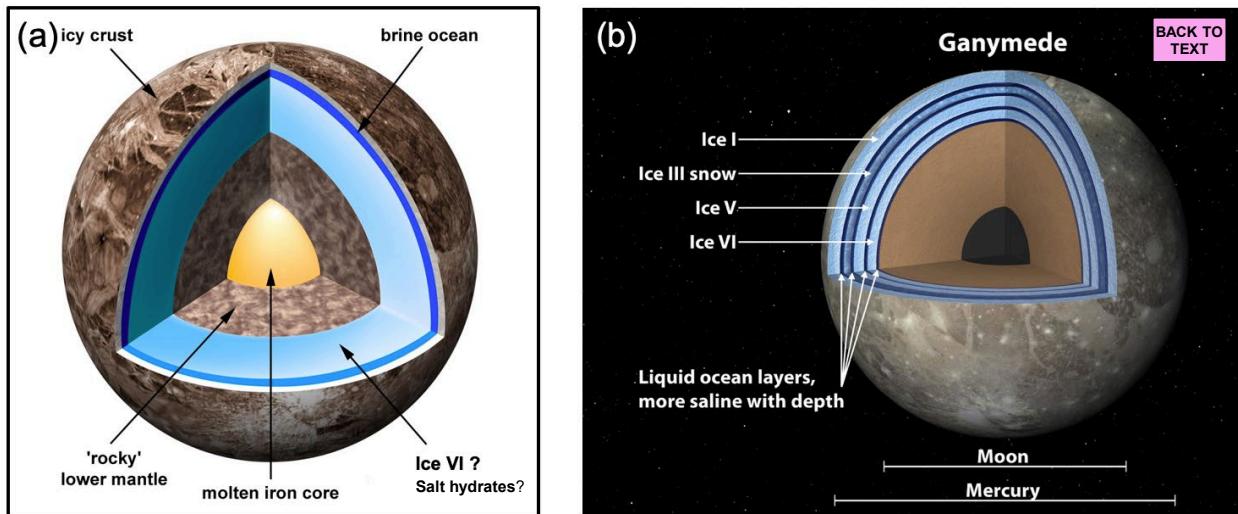
### 3. Ganymede and Callisto

Ganymede and Callisto are also thought harbour sub-surface oceans (Fig. 8). However, they would be expected to be much less hospitable for life than Europa's ocean because:

- Less tidal heating is expected and so there is a lower probability of hydrothermal activity;
- Any sub-surface 'oceans' are probably not in direct contact with the silicate mantles owing to a layer of dense, high-pressure ice (ice VI; see Fig. 8), preventing serpentinization reactions from occurring (although the 'sandwich model' (Fig. 8(b)) might allow the innermost ocean layer to be in contact with a silicate mantle);
- The lack of surface manifestations of any recent interchange between the surface and subsurface oceans means that there is no mechanism for the delivery of surface-derived oxidants and organics to the interior.

Clearly, any of these oceans will be very difficult to access in practice.

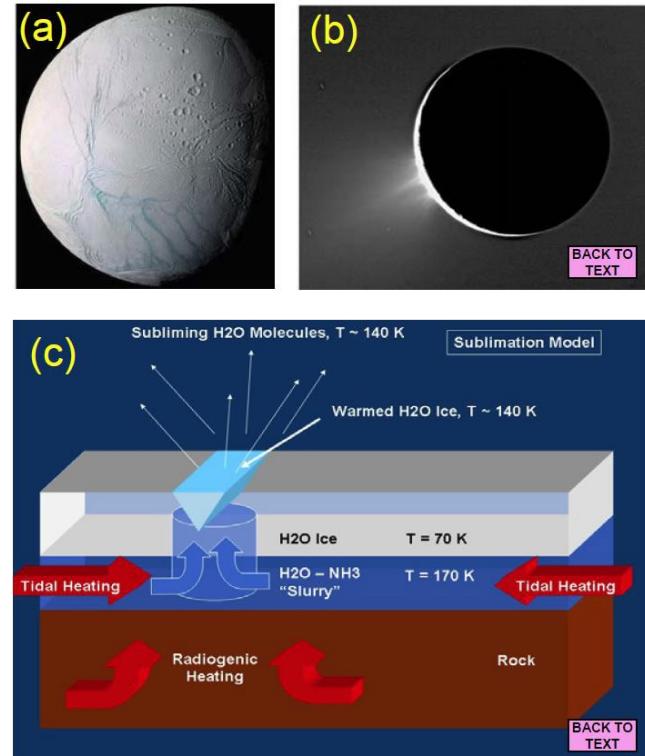
**Fig. 8.** Two different models for the interior of Ganymede. **(a)** a saline ocean layer trapped between the icy crust and a dense layer of ice VI and/or salt hydrates (courtesy Dominic Fortes). **(b)** The 'sandwich model' where several saline ocean layers are trapped between different phases of ice; the lowermost layer may be in contact with the silicate mantle (NASA).



## 4. Enceladus

Shortly after the Cassini spacecraft arrived at Saturn in 2004 it was discovered that the small moon Enceladus (diameter ~500 km; Fig. 6(a)) is venting plumes of material into space from fissures in its south polar region (Fig. 6(b)). Subsequent analysis has revealed that these plumes consists of water vapour and small ice crystals, together with small quantities of N<sub>2</sub> (~4%), CO<sub>2</sub> (~3%) and CH<sub>4</sub> (~1.6%). In 2017, H<sub>2</sub> was detected in the plumes, providing evidence for serpentinization reactions between liquid water and a silicate mantle (J.H. Waite et al., *Science*, [356, 155, 2017](#)). These observations imply that Enceladus contains a potentially habitable sub-surface ocean. A possible model is shown in Fig 9(c): the energy required to melt the ice comes from a combination of tidal and radioactive heating, and the freezing point of water may be lowered by dissolved ammonia and/or other solutes. Such a sub-surface ocean could be habitable for chemosynthetic microorganisms deriving their energy from H<sub>2</sub> and CO<sub>2</sub>.

In 2018 the Cassini mass spectrometers detected evidence for large (>200 amu) organic molecules in the ice grains entrained in the plumes, interpreted to originate in an organic-rich film at the top of the water table (F. Postberg et al., [Nature, 558, 564, 2018](#)). These observations further support the habitability of the sub-surface of Enceladus. Future observations might include measurements of the carbon isotope ratios in the plumes' CO<sub>2</sub> and CH<sub>4</sub>, which may be different if the latter has a biological origin, and direct sampling of the plumes for return to Earth for analysis.

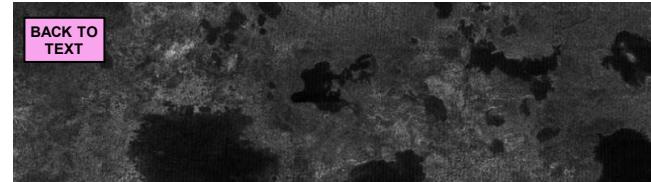


**Fig. 9.** (a) Enceladus showing 'tiger stripes' at the south polar region; (b) Plumes venting water into space; (c) A model of the interior of Enceladus (NASA/JPL).

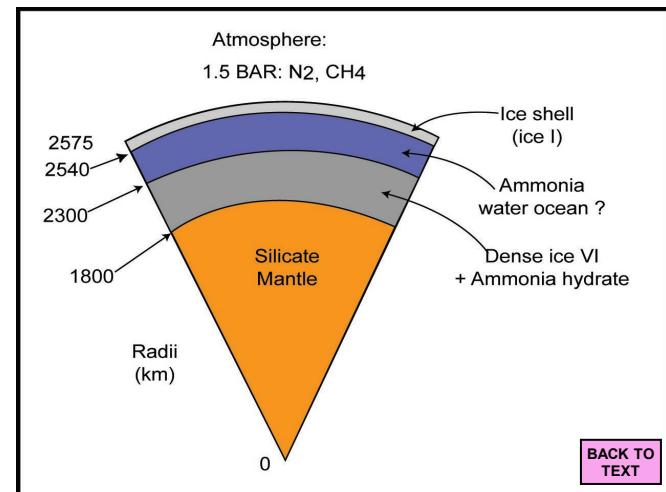
## 5. Titan

Titan is the largest moon of Saturn, with a radius of 2575 km, and an average density of 1.9 g/cm<sup>3</sup>. Its internal structure and composition may be similar to those of Ganymede and Callisto. However, the presence of a dense, mostly nitrogen, atmosphere sets it apart from all other satellites in the Solar System. It has been known since the Voyager flybys of 1980/81 that Titan is obscured by a haze of organic molecules produced by the photodissociation of methane (CH<sub>4</sub>), which is present at a concentration of between 1 and 6%. Complex organic precipitates (“tholins”) are thought to accumulate on the surface. In addition there is clear evidence for lakes of liquid CH<sub>4</sub> and ethane at high latitudes (Fig. 10). Titan is therefore of great interest from the point of view of prebiotic chemistry – it is essentially a giant, natural Urey-Miller experiment. However, with a temperature of  $-180^{\circ}\text{C}$ , the surface is almost certainly too cold to support any actual biological activity (which would in any case have to be based on hydrocarbon solvents rather than liquid water).

Most speculations concerning life on Titan depend on the presence of a warmer, sub-surface ocean. Theoretical calculations suggest that Titan also has a sub-surface ocean, similar to those thought to exist within Ganymede and Callisto (Fig. 11).



**Fig. 10.** Cassini radar strips of the surface of Titan at a latitude of about 80° N. Dark irregular areas of low radar reflectivity are interpreted to be hydrocarbon lakes. Image size is 150×420 km (NASA).



**Fig 11.** Possible internal structure of Titan. Note possible (but not yet confirmed) presence of a liquid water-ammonia ‘ocean’ sandwiched between two layers of ice. (Courtesy Dr. Dominic Fortes; see *Icarus*, vol. 146, p. 444; 2000).

The presence of a sub-surface ocean is supported by Cassini measurements of the tidal distortion of Titan as it orbits Saturn, and observations of possible 'cryo-volcanism' on the surface are consistent with this model of the interior. The habitability of any such ocean will depend on the existence of sources of energy and organic molecules, and would be facilitated by exchange of matter with the organic-rich surface. Such an interaction could be mediated by convection in the thick overlying shell of ice and/or cryovolcanism, for which there is some evidence. Direct interaction between an ocean and the underlying rocky mantle (e.g. through hydrothermal vents) seems unlikely as theory suggests that the 'ocean' will be separated from the mantle by a thick layer of dense Ice VI (Fig. 11). However, if CH<sub>4</sub> is continually being outgassed (which may be necessary to balance photodissociation) then channels through the ice layers may be implied.

## **6. Other potentially habitable Solar System bodies?**

Other locations in the Solar System where water exists in a solid form, and where sub-surface environments may permit liquid water to occur, at least transiently, include: permanently shadowed craters on Mercury and the Moon, hydrated asteroids (e.g. Ceres), lava tubes on Io, minor moons of the giant planets, Pluto (for which the New horizon flyby in 2015 found tentative evidence for a sub-surface ocean) and other Kuiper Belt objects, and comet nuclei. We should also bear in mind that Venus may have had a habitable surface environment before its runaway greenhouse effect became established (see Section 7.2, below). Some of these Solar System objects and locations are more worthy of investigation from an astrobiology perspective than others, but they generally have a lower priority than Mars, Europa, Enceladus and Titan when it comes to funding space missions.

We should also recognize that there are potentially habitable environments within planetary atmospheres, to which we now turn.

# 7. Planetary atmospheres

## 7.1 Giant planet atmospheres

Historically, most speculation has concerned the cloud decks of the giant planets, especially those of Jupiter (Fig. 12). The structure of Jupiter's atmosphere is summarised in Figure 13, which reveals a region about 50 km below the visible cloud tops where liquid water droplets are expected to form clouds.

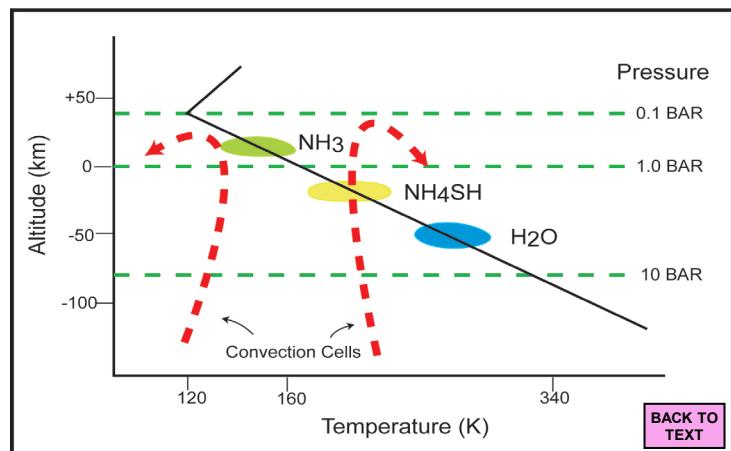
The pressure in this region is about 5 bars, and the temperature about 10°C. These conditions are well within the range known to permit life on Earth. The multi-coloured clouds above this level are thought to consist of organic molecules produced by solar ultraviolet light, in a similar manner to what is found on Titan, so a source of organic molecules may also be available.

This region of Jupiter's atmosphere is not currently favoured as a possible abode of life, mainly because the region is expected to be subjected to strong vertical convective motions, which would rapidly sweep any microorganisms into much less hospitable above and below this thin, temperate layer (Fig. 13). However we don't really know that this would preclude the origin and evolution of life in this environment, and should probably keep an open mind.



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**Fig. 12.** The southern hemisphere of Jupiter imaged by Voyager 1. Note the multi-coloured clouds which are thought to contain organic molecules (NASA).



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**Fig. 13.** The temperature structure of Jupiter's upper atmosphere, showing the different levels at which clouds are expected to form. The dashed lines indicate vertical convective motions which may make these atmospheric layers non-conducive to life.

## 7.2 Venus' atmosphere

We don't know when Venus (Fig. 14) first developed the runaway greenhouse effect that makes the present surface uninhabitable. However, some models of habitable zone evolution suggest that early Venus may have lacked a greenhouse effect and have had liquid water on its surface.

It has therefore been suggested that any life that had evolved on Venus before the greenhouse effect took hold might have migrated to the thick cloud layers which surround the planet.

Within the cloud layers, at an altitude of ~30-50 km (Fig. 15), temperatures are amenable to life (-10 to +75°C). However, water is thought to be very scarce, and the only liquid medium appears to be the sulphuric acid cloud droplets. Whether life is possible in this environment is unknown. However, the question has received renewed attention with the recent discovery of phosphine gas ( $\text{PH}_3$ ) in the upper cloud decks (Jane Greaves et al., [Nature Astronomy, 2020](#)).  $\text{PH}_3$  has been suggested as a biomarker for exoplanet atmospheres because there are few non-biological ways to produce it in a terrestrial planet atmosphere. Determining whether the  $\text{PH}_3$  in Venus' atmosphere is due to life, or is the result of unanticipated atmospheric chemistry, is certain to become a major topic of research.



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Fig. 14. The clouds of Venus (NASA/JPL)

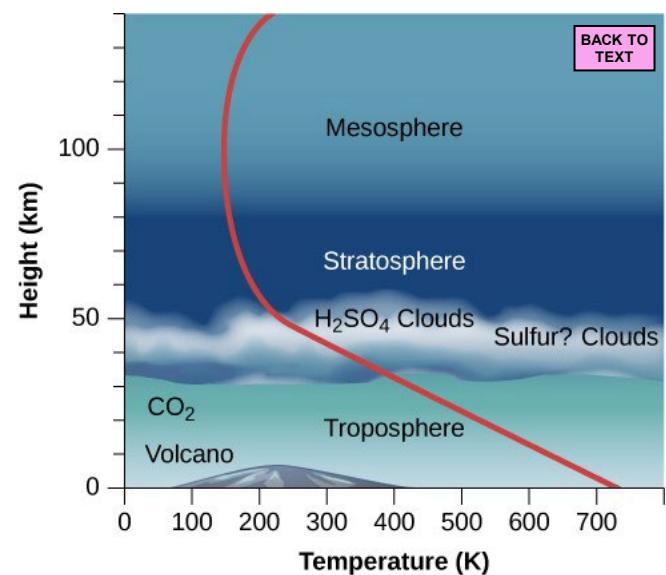


Fig. 15. The structure and temperature profile of Venus' atmosphere ([Lumenlearning.com/CC-BY](#)).

## 8. Panspermia: Can life travel between planets?

We saw above that meteorites are able to deliver organic molecules to the surfaces of terrestrial planets. Sometimes it has been suggested that life itself may have been delivered to Earth (and other planets) in the same way, a hypothesis known as ‘panspermia’ (which literally means ‘seeds everywhere’). Of course, panspermia doesn’t solve the problem of the origin of life (which is why many workers in the field dislike it), but it might provide a wider range of possible locations and, depending on that location, a little more time for abiogenesis to occur.

One of the first scientists to take an interest in the idea was the physicist William Thomson, later Lord Kelvin, who devoted part of his Presidential Address to the British Association for the Advancement of Science to the topic in 1871, writing:

“because all we confidently believe that there are at present, and have been from time immemorial, many worlds of life besides our own, we must regard it as probable in the highest degree that there are countless seed-bearing meteoric stones moving about through space. [...] The hypothesis that life originated on this earth through moss-grown fragments from the ruins of another world may seem wild and visionary; all I maintain is that it is not unscientific.”

Here, we will here consider the possibility that life might be transported between planets in our own Solar System on meteorites (sometimes called ‘lithopanspermia’) as Thomson envisaged, and leave the more speculative question of panspermia between separate planetary systems to Lecture 10.

To-date (September 2020) almost three hundred Mars meteorites have been found on Earth, so the interplanetary transfer of material is certainly possible. The only question is whether life can survive the journey. Three stages of this journey need to be considered:

## (a) Ejection from a planetary surface by meteorite impact

Meteorites that are blasted into space by the impact of a larger meteorite on their parent planet are exposed to a number of extreme conditions:

- Extreme acceleration ( $\approx 10^5$  g)
- High pressures due to shock ( $\approx 10^5$  bar)
- Shock-induced heating (typically  $>100^\circ\text{C}$ )

However, while extreme, these conditions only last for a very short time, typically a thousandth of a second. Laboratory studies have shown that bacterial spores can survive these conditions, although active bacteria probably cannot. In one study, a fraction of  $10^{-4}$  *Bacillus subtilis* spores survived a 300,000 bar shock, and a  $250^\circ\text{C}$  post-shock temperature. As a 1 kg meteorite derived from Earth's near surface might contain  $\sim 10^{11}$  spores, this would still leave ten million survivors!

## (b) Survival in space

Bacterial spores are metabolically inactive, and so do not require either liquid water or a supply of energy. The main danger they are exposed to in space is radiation, especially as their repair mechanisms are also shut down. Experiments in space have demonstrated high survival rates, provided that the spores are protected from solar ultraviolet light. For example, after six years exposure on NASA's Long Duration Exposure Facility (LDEF; Fig. 16) 67% of *B. subtilis* spores were found to have survived the space environment (e.g. vacuum and extremes of temperature) if shielded from the UV.



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**Fig. 16.** NASA's Long Duration Exposure Facility (LDEF), on which a range of bacterial spores were exposed to the space environment for six years before being retrieved by the Space Shuttle (NASA).

Laboratory experiments imply that ~99% of spores are rendered unviable within seconds if not protected from solar UV, but only a very thin (<1mm) covering of meteoritic material is required to shield from UV radiation.

Similar results have recently been obtained in experiments on the International Space Station (Fig. 17; reported by [Kawaguchi et al., \*Frontiers in Microbiology\*, 2020](#)), where samples of the bacterium *Deinococcus radiodurans* remained viable after three years exposure to the space environment, provided they were located within cell aggregates greater than 0.5 mm thick so that overlying cells provided radiation protection.

Thus, microbial cells and/or spores located within the body of a meteorite would be well protected from Solar UV, and are likely to survive many years of exposure. High-energy cosmic rays, which will penetrate up to a meter of rock, cannot plausibly be protected against, and set the ultimate radiation limit for the survival of microbial spores in space. However, relative to the size of a microbial spore, cosmic rays are relatively rare, and a typical spore could survive in space for ~ a million years before being impacted. As the transit times for meteorites moving between terrestrial planets is also of the order of a million years, many spores are likely to escape being hit by a cosmic ray particle during transit. The duration of transit in interplanetary space for other star systems is likely to vary depending on the architecture of the system, but in some cases (e.g. [TRAPPIST-1](#)) there would be much shorter transit timescales involved.



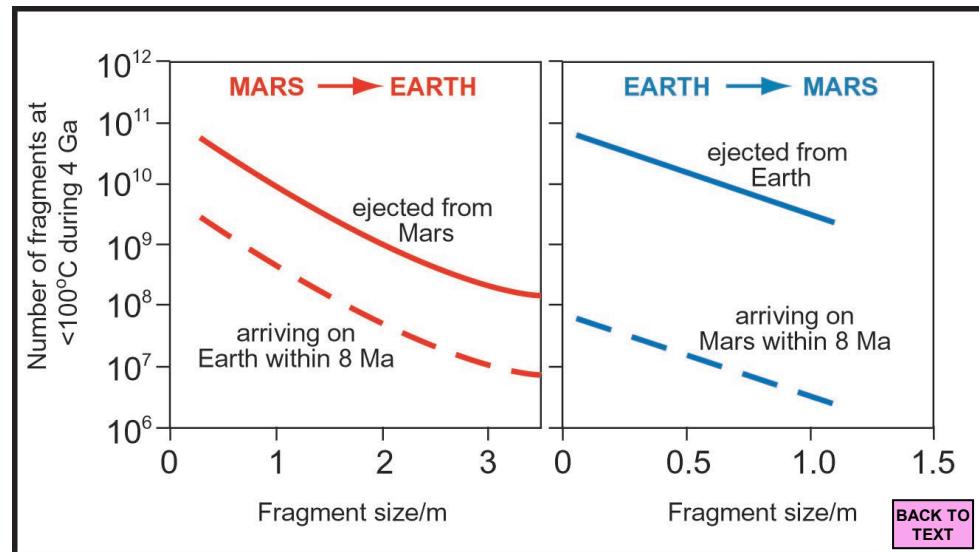
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**Fig. 17.** The Japanese Kibo module attached to the ISS (left) and the 'Exposed Facility' (right) where the panspermia experiments reported by Kawaguchi et al. (2020) were performed (NASA).

Fig. 18 shows theoretical calculations of the numbers of meteorites that are likely to have been exchanged between Earth and Mars over the last 4 billion years, as a function of meteorite size. Note that these figures just relate to meteorites shock-heated to temperatures less than 100°C, and on which life might therefore survive. The diagram also shows the number which will have had relatively short transit times (< 8 million years). Note that the numbers of meteorites exchanged could have been ten times higher prior to 4 billion years ago, during the period of heavy bombardment.

### (c) Landing

Large meteorites, which are not decelerated significantly by the atmosphere, undergo hyper-velocity impacts with the surface and produce impact craters. As most of such meteorites are vaporized on impact, survival of any micro-organisms within them is probably impossible. However, smaller (i.e. metre-sized) meteorites are decelerated when they enter a planetary atmosphere. Although the outer layer is severely heated by atmospheric friction, the resulting ‘fusion crust’ only extends for about 1 mm into the meteorite, and the interior is unaffected. Survival of micro-organisms in the interior of such a meteorite should therefore be straightforward.



**Fig. 18.** Theoretical calculations showing the number of meteorites exchanged between Mars and Earth, and Earth and Mars, over the last 4 billion years. These calculations are restricted to those meteorites that have been shock-heated to less than 100°C, and the lower (dashed) curves show the numbers of these having relatively short transit times (<8 million years). During the period of heavy bombardment, between 4.5 and 4.0 Gyr ago) the numbers of meteorites exchanged between planets may have been much higher. (Adapted from Mileikowsky et al., *Icarus*, 145, 391, 2000).

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Thus, although there is still great uncertainty about the long-term survival (i.e. over millions of years) of bacterial spores in space, it appears that interplanetary lithopanspermia may indeed be possible within relatively small meteorites exchanged between planets. There are some important astrobiologically important implications of this conclusion:

- If evidence for past or present life is found on Mars (or anywhere else in the Solar System for that matter) we would need to determine whether it evolved independently, or was just a colony of terrestrial life. An independent origin would carry with it the implication that life is probably common throughout the Universe, it having evolved more than once in just one planetary system. However, it would not be possible to draw this conclusion if all life in the Solar System has had a common origin, as then the origin of life event itself could then still be unique.
- Given that other locations in the Solar System (e.g. Mars, the icy moons in the outer Solar System, perhaps even Venus!) may have had a head start on the Earth (e.g. faster accretion of smaller planetary bodies; no Moon-forming giant impact) we would need to consider carefully the possibility that life may not have originated on Earth.
- Interplanetary transfer of materials, and possibly life, is unlikely to be limited to the Solar System. A [2017 paper by Lingham & Loeb](#) estimated that the rate of interplanetary transfer to be ‘orders of magnitude’ (tens to hundreds of times) greater, and the transit durations much shorter, for planets orbiting the small M-dwarf star TRAPPIST-1 than in the Earth-to-Mars scenario.