THE POSSIBLE SITES FOR EXOBIOLOGICAL ACTIVITY ON TITAN

Michael B.Simakov

Group of Exobiology, Institute of Cytology RAS,
Tikhoretsky Av. 4, St.Petersburg, 194064, Russia
tel.:+7 812 2477450/fax:+7 812 2470341; e-mail: exobio@usa.net

ABSTRACT

Titan, the largest satellite of Saturn, is currently the most favorable site for search of extraterrestrial life. This moon is one of the Solar system bodies, which could have a large quantity of liquid water. The putative internal ocean along with a rich dense atmosphere provide some new exobiological niches: (1) the upper layer of the internal water ocean; (2) water pockets and liquid veins inside icy layer; (3) the places of cryogenic volcanism; (4) set of caves in icy layer connecting with cryovolcanic processes; (5) the brine-filled cracks in icy crust caused by tidal forces; (6) liquid water pools on the surface originated from meteoritic strikes; (7) the sites of hydrothermal activity on the bottom of ocean. All conditions needed for exobiology - liquid water, complex organic chemistry and energy sources for support of biological processes - are on Saturnian moon.

INTRODUCTION

Saturnian moon Titan is one of the Solar system bodies, which could have a large quantity of liquid water. Data obtained by the *Galileo* spacecraft indicate the possible existence of the salty liquid-water oceans inside Jupiter's moons Europa [1], Callisto [2] and Ganymede [3,4]. Theoretical models of Titan's interior also predict an existence of substantial liquid layer, as much as 350 km thick, under relatively thin (less than 80 km) water ice cover [5, 6]. During the first period after accretion ($\sim 10^8$ years) Titan could have a salty-rich warm ocean on the surface owing to accretional heating [7] and a dense CO_2-N_2 atmosphere which was at least 30 times greater than its present value [8]. The first stages of the chemical evolution would have took place in these ocean and atmosphere under the action of such energy sources as ultraviolet radiation, solar wind, galactic cosmic rays, magnetospheric plasma ion bombardment, electrical discharges, radiogenic heat and so on. Besides, the great part of organic matter may have been acquired from cometary and chondritic material. Two sources of volatiles for primordial Titan's atmosphere are plausible: planetesimals that condensed within a Saturnian subnebula and eventually accreted to form Titan, and comets that condensed outside the Saturnian subnebula. The rich atmosphere we see today is actually a combination of impact delivery and degasing of interior [8]. Comets could provide Titan with a great quantity of H_2O, CO, CO_2 and N-bearing compounds [9]. During a period of the heavy bombardment NH_3 from the primordial atmosphere would have rapidly been removed through the forming of N_2 with subsequent production of NO followed by reactions leading to NO_2^- and NO_3^-, which would have accumulated in the ocean. Such scenario has been described for the evolution of nitrogen cycling on Earth [10] and similar processes could be proposed for the early history of Titan's atmosphere. Recent attempts to establish a lower limit for the time required for emergence of life suggest that 10-100 million years was enough in case of Earth. During the phase of cooling ($\sim 10^8$ years) Titan's ocean was roofed over with ice crust. If life had originated by then, they could survive in the some places up to the present [11]. In other case the variety of prebiotic processes can take place on Titan. The composition of the rich atmosphere which is host to extensive organic photochemistry and internal liquid layer must be very complex and Titan's putative ocean might harbor life or prebiotic structures. The main scientific attention devotes now to the complex photochemistry in Titan's atmosphere which is widely considered as a model of Earth's primordial atmosphere [12]. The existing of liquid ocean gives more exobiological niches.

EXOBIOLOGICAL NICHES

The most appropriate sites for biological and/or prebiological activity at present day are: (1) the upper layer of the internal water ocean when a temperature and pressure are suitable for living processes and a cycle of freezing-thawing can serve as a concentration mechanism and generate electric potentials for accelerate of reactions; (2) water pockets and liquid veins inside icy layer; (3) the places of cryogenic volcanism; (4) macro-, mini- and microcaves in icy layer connecting with cryovolcanic processes; (5) the brine-filled cracks in icy crust caused by tidal forces; (6) liquid water pools on the surface originated from meteoritic strikes; (7) the sites of hydrothermal activity on the bottom of ocean.

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The upper boundary of ocean and ice crust.

The multicomponent composition of the oceanic water on Europa and Ganymede has been detected by *Galileo* [1,4]. Titan's ocean likely contains also an array of endogenic materials incorporated into the satellite during its formation and released during planetary differentiation, including considerable organic compounds [13], which could help support life there. Since the light energy in form of solar radiation is not accessible in such conditions (the solar flux to Titan's surface is ~1.1% from Earth's one) the chemical energy has to be the main source which drives the life and other disequilibrium processes. So, the initial components for lithoauthotrophic processes, such as NO_3^-, SO_4^{2-}, CO_3^{2-} could exist in the Titan's putative ocean and provide biologically useful electron donor-acceptor pairs in the upper layer. Nitrate accumulated in the ocean at the first stage of satellite's evolution would have allowed the first protobiosystems to use it as the source of energy. We would like to propose the idea that the first protoliving systems had internal energy source, namely, the chemical potential of an inorganic reaction. The high probability is that the first living systems had evolved from set of Belousov's redox reactions. The basic reaction of nitrate reduction $NO_3^- \rightarrow N_2$ is a more thermodynamically favorable in the row of different inorganic substrates [14]. Electron donors that may be important in such process include Fe(II), pyrite, sulfur compounds and organic material [15]. Although reduction of nitrate by Fe(II) is thermodinamically feasible, this reaction is not occurring spontaneously, but it is ready catalyzed. The all gaseous nitrogen in the contemporary Titan's atmosphere can be the product of this reaction [16]. At the other hand Fe(III) oxyhydroxides are readily reduced by H_2S and various organic acids. On Earth microbial Fe(III) reduction is major way of organic carbon oxidation in anaerobic environment [17]. The production of reduced end products, e.g. Fe(II), FeS be Fe-reduction and H_2S by sulfate reduction could resupply the basic reaction with reagents. So we can imagine a biogeochemical cycle for maitain of the ecosystem. This cycle would demand only a few flow of external energy and reagent sources. The reaction of nitrate/nitrite reduction could have served not only as an energy source but as a source of reduced (or "fixed") nitrogen compounds, which are essential for the synthesis of biologically important ones. For example, the Strecker synthesis and the Fe(II) reduction of nitrate to ammonia can be combined to form of amino acids from nitrite, Fe(II), cyanide, and formaldehyde [18]. The lithotrophic iron oxidizers that use Fe^{2+} as an energy source for their metabolism and use nitrate as an electron acceptor have been recently described [19].

Water pockets inside lowest part of the ice layer

Complete freezing of H_2O-salts system occurs at ~–45°C [20]. The formation of ice during freezing leads to concentrate of the impurities both organic and inorganic. Thus the very small portion of the initial volume likely remained unfrozen and consisted of highly concentrated brines of different compounds. Simultaneously, a continuous network of aqueous veins could be formed in the lowest layer of the ice. The ions (SO_4^{2-}, HSO_4^-, NO_3^-) from solution are concentrated in these veins also [21]. Eutectic freezing is the most promising concentration mechanism. The potential prebiological or protobiological chemistry could exist in such environment [22], and this network could be a good microbial habitat. The liquid water, main electron acceptors and carbon source are in these environments. The ice is a good habitat for life on Earth. Microbes, some of which may be viable, have been found in ice cores drilled at Vostok Station at depth down to ~3.600 m [23]. The living processes could run as long as liquid water is stabilized by solutes. The lower part of the Titan's ice crust could provide a good habitable niches both for many forms of the Earth's life and for any domestic forms. This layer could be highly porous and extremely permeable for oceanic water containing electron acceptor and donors to create an energy flows. The Earth's brines tend to migrate within solid sea ice due to temperature and concentration variations, density/buoyancy characteristics, and the resulting gravity gradients. The brines can be distributed throughout sea ice, making up volume percentages typically 5-40%. So, the brines could transport substances and heat inside the ice layer.

Liquid volcanism.

The cryovolcanic activity is a common phenomenon in the Solar system and it has been detected on Europa, Ganymede [24], Tritone and Uranian moons [25]. Given the observation of ice volcanism on so many outer solar system satellites, it seems logically to assume the similar processes for Titan [26]. It is seems feasible that volcanism could continue up to the present. Cryolava (water-methanol solution containing abundant salts, such as NH_4Cl, $(NH_4)_2SO_4$, NH_4NO_3 and others) which has a eutectic melting point of 176 K could act as the link between interior and surface and form a large net of caves. Such fluids are very hot by Titan standards. Under Titan's conditions such ice/water mixtures might behave in similar ways to silicate magmas. The characteristics of cryomagmatic materials have great potential variety, depending on the thermal state and pressure, amount and composition of contaminants. Melt-through episodically produces open pools of liquid and the products of complex atmospheric organic chemistry could be melted by this fluids or dissolve in it. Such pools have a range of temperatures, chemical and physical states, and mixing processes. The resurfacing of Titan can occur through eraptions of water, possibly in combination with various other nonwater components in a solid, slushy, or liquid state.

Icy caves

Subsurface cavities connected with cryovolcanic processes could provide a huge array of habitats. These caves could be both with external entrance and closed systems (plutonism). Lorenz and Lunine [27] found that a karst landscape could develop involving subterranean caverns and passages. The liquid hydrocarbons from surface could soak into the caves connected with cryovolcanism and form complex interphase systems mixing with the cryolava. Here we can propose a new kind of prebiological chemistry - inverted interphase catalysis - micelles existing in hydrocarbon fluids, which is expected to be very rich in organic solutes, and having an aqueous solution of minerals and small organics inside. These structures both have an ability to concentrate molecules and have membrane-like components which are able to use membrane potential and/or ion gradients for the protometabolism. Caves, subsurface fissures, microcracks all could provide homes for microbial life. The subsurface offers one of the best of all possible site for exobiological activity when the environments could be the less hazard then on the surface. The caves could also preserve of the possible biosignatures owing to relatively stable environments over long geological periods. These caves also could provide a more easy access to the internal part of the upper ice crust.

Brine-filled cracks

Cracks in the icy crust caused by tidal forces has been proposed for Europa [28]. Such features could exist on Titan and serve as the mechanism for transporting and mixing substances vertically. Acting as a pump these cracks could deliver complex organic substances from Titan's atmosphere to internal ocean. So, we can predict the niches in the ice crust periodically bathed in liquid water. The heat could be generated within the active cracks. As a result of tides liquid water regularly bathed crustal cracks and surfaces with heat, transporting and mixing substances from the oceanic reservoir and surface. Within a given crack, any organisms would be expected to occupy a range of depths, with individuals either moving with the flow or attaching themselves to the crack wall for as the wall remained solid. Here the organisms could exploit the range of conditions and available substances. Thermally induced solid-state convection within ice shell could also circulate subsurface material between the ocean and the surface and provide a significant amount of biogenic compound to sustain an internal biosphere. Individual cracks may remain active for at least tens of thousands of years. [28]. The brine-filled cracks in Earth's sea ice [29] or in the lithosphere [30] provide a suitable habitat for microorganisms and these types of environments may offer close parallels with the cracks in the Titan's ice shell.

Liquid water pools on the surface

The large meteoritic collisions could temporary melt a large amount of surrounding ice. This melt water has to have a complex organic compounds derived from atmosphere, both unpolar (hydrocarbons) and polar (nitriles). Up to 1 km of organic sediments may blanket Titan's surface [31]. These mixtures of unpolar, polar and amphiphile molecules could form more complex structures, such as micelles, inverted micelles and other interphase surfaces. The evolution of these structures could result in the formation of double layered membranes similar to biological ones. Such liquid pools could exist more then 10^3 years [32] and serve as a connection between complex atmospheric chemistry and internal water one. The time are long enough for different processes of chemical evolution. For example, the hydrolysis of some types of Titan's tholins releases amino acids [33], and the nucleic acid bases also could be synthesized in such conditions [22]. Impact of cometary or meteoritic bodies should also provide a source of biologically useful compounds at these pools. After freezing the complex structures could be intact on ice. The structures that do become embedded in the ice would have a good chance of being thawed and liberated later under the next melt event. So, there can be cyclic evolution of complex prebiological structures in the upper ice layer. Besides, some of the previous mechanisms could deliver these structures down to the ocean.

Hydrothermal vents

The release of heat from Titan's core could be accompanied by magma degassing and hydrothermal activity. Several abiotic processes could lead to synthesis of organic compounds and supply them to putative ocean: (1) Fischer-Tropsch type (FTT) synthesis from cooling volcanic gases [34]; (2) aqueous synthesis in mixing zones of hydrothermal fluids and with oceanic water [35]; (3) aqueous FTT synthesis during initial stages of chemical interaction of oceanic water with basic/ultrabasic igneous rocks [36]. Hydrothermal reactions between the ocean and underlying rock layer should have reprocessed a portion of the ocean, along with infalling cometary and chondritic material, into more complex organic compounds. Hydrothermal vents could support the carbon cycle [37], but high pressure on the bottom of ocean decrease the stability of the biogenic material under hydrothermal processing. So we can consider the hydrothermal activity in such conditions only as a source of disequilibrium into subsurface ocean and initial simple organic compounds to support of prebiotic metabolism in upper layers of the ocean.

CONCLUSIONS

The environments mentioned above indicate that conditions capable of supporting life are possible on Titan. All requirements needed for exobiology -- liquid water which exists within long geological period, complex organic chemistry and energy sources for support of biological processes are on Saturnian moon. The existence of rich atmosphere is the main difference from Jupiter's moons. This atmosphere could supply the large quantity of different organic compounds to putative ocean. There are some possible mechanisms for extensive, intimate interaction of a liquid water ocean with the surface of the ice crust. Titan provides insights regarding the geological and biological evolution of early Earth during ice-covered phase. There are a huge deficiency of carbon in the contemporary environment and this disappeared carbon could be contained as biomass and dissolved organic carbon in putative ocean. Possible metabolic processes, such as nitrate/nitrite reduction, sulfate reduction and methanogenesis could be suggested for Titan.

The existing of the ocean inside Titan may be constrained from Cassini flyby data, but detection of the signs of life on surface or in that ocean will demand new, more complicated missions [38]. Future Titan missions will wish to study the samples in-situ. There are several places for our search:

- The main attention should be paid to cratered regions which could contain signs of recent water activity after meteoritic strikes.
- The search for network of cavities using subsurface sounding radar could give information on place which might be of special interest in a search for life.
- Subsurface sounding radar could also identify areas with recent cryovolcanism has occured (Cassini also would be able to resolve the volcanic features [39]), and in turn where aqueous/organic chemistry may have occurred. Organisms and biogenic compounds could be erupted with these fluids onto the surface also.
- Contemporary volcanic activity ought to be rather easy to detect. The Cassini Visible and Infra-Red Mapping Spectrometer (VIMS) will map parts of the surface. An ammonia-water cryomagma will emit twenty times more radiation than the surrounding landscape (~94K) at 5.1 μm.
- The search for thermal anomalies also could give information about active cracks which may have biological signatures.
- The $^{15}N/^{14}N$ atmospheric ratio could be considered as a potential biomarker, since the isotopic fractionation of nitrogen has to take place in prebiotic systems.

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