Saturn's Titan: A Strict Test for Life's Cosmic Ubiquity

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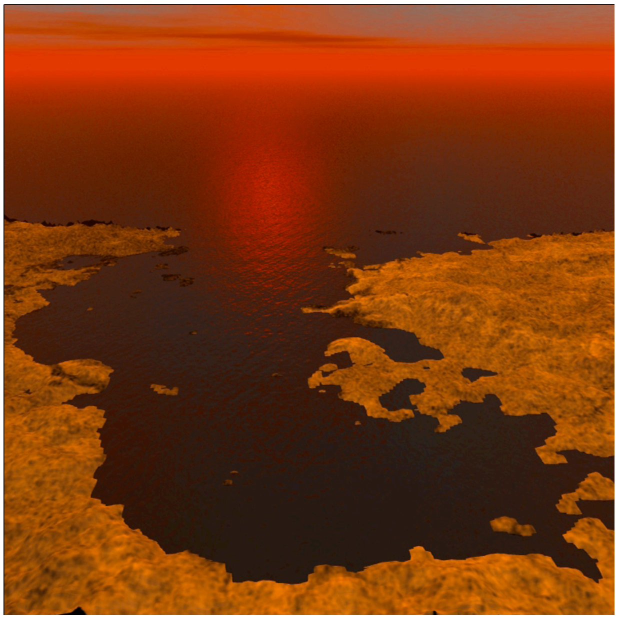

Titan Mare Visualization by R.L.Kirk

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Introduction

Is life a common outcome of physical and chemical processes in the universe? Within our own solar system, a successful search for even primitive life, *were it to have an origin independent from life on Earth*, would dramatically advance a positive answer (1). The most stringent test for a second independent origin of life would come from examination of either the most physically remote from Earth, or the most exotic type, of planetary environments in which one might plausibly imagine a form of life could exist. In this paper I argue that Saturn's moon Titan is the best such target in our solar system and might be a type example of a planetary environment abundant throughout the cosmos.

The second-largest moon in the solar system, Titan has a nitrogen-rich atmosphere four times denser at its surface than Earth's (2), a wealth of organic molecules in the atmosphere and on the surface (dominated in the atmosphere by methane) (3), and a "hydrologic cycle" in which methane is the main working fluid (4). The joint US-European mission called "Cassini-Huygens" has, since 2004, mapped Titan's surface with imagers, radar, the Huygens descent probe, and other instruments, revealing the presence of equatorial dunes made of organic particles, channels carved in what is probably a water-ice landscape, and high latitude lakes of methane and ethane (5). This exotic landscape—water ice geology carved through the action of liquid methane and ethane—is the result of Titan's large size and great distance from the Sun, stabilizing the atmosphere and ensuring a very cold (-179^{o} Celsius) environment suitable for liquid methane and ethane.

Such conditions, in which water is completely frozen-out and present as liquid only for short times after meteorite impacts and geologic heating events, would seem unfavorable for life. And, indeed, for life as it is known to exist on Earth—life that requires liquid water—only a possible liquid water layer deep beneath Titan's ice crust would seem habitable (6). Such a layer is unreachable given the present-day crustal thickness at or exceeding 50 km by most estimates, although clues to the presence of life might come from chemical and isotopic anomalies (7). Alternatively, one might ask whether the terrestrial biological requirement for liquid water is too restrictive. Could the liquids that are stable at Titan's surface—methane and ethane—play host to a form of organic chemistry that would include all the attributes we associated with life? Such a form of life would be so different from terrestrial life that one would be forced to conclude it had an independent origin.

The possibility of life in hydrocarbon lakes on Titan

The hundreds of lakes seen on Titan by the Cassini orbiter instruments cover approximately 15% of Titan's known surface above 65^{o} north (only about half of this north polar region has been imaged), and less in the southern hemisphere (8). However, this is a substantial physical area, given that Titan is larger than the Earth's moon, and the three largest lakes are referred to as "mare" (Latin for "sea") by the International Astronomical Union in recognition of their size. While the evidence for liquids in the lakes and seas is circumstantial, it is compelling and derived from several distinct types of observations (9). The seas may be tens of meters deep based on their very dark appearance to the radar system onboard Cassini (9).

The ambient conditions on Titan are such that the dominant constituents of the lakes and seas are likely to be liquid ethane and methane, with a small admixture of nitrogen from the atmosphere and organic molecules that rain down continuously into the lakes from high altitudes where solar ultraviolet rays and charged particles from the Saturn environment act on the methane. Thus, Titan's lakes and seas are quite different from those of the Earth, but they are bodies of liquid nonetheless, and the largest should be stable for very long periods of time. There is even the possibility that the seas are connected to an even larger subterranean body of liquid methane, ethane, or both (8).

Could such lakes and seas, containing hydrocarbon liquid rather than water, host something that might be considered life? Much of the work to address this question has been done by S. Benner and his colleagues (10), and the rest of this section is a summary of their conclusions. Because all life on Earth requires liquid water, and indeed the fundamental polymers of biology—proteins and the nucleic acids—require intimate contact with liquid water for their proper functioning, it is assumed that liquid water has properties that make it especially suited for life. Indeed, water is liquid over a broad range of temperatures, and water ice floats on liquid water providing an insulating effect when temperatures hover around freezing. Water forms bonds between its oxygen atom and a hydrogen atom in a neighboring water molecule ("hydrogen bond") more readily than it does with most organic molecules. This allows the formation in water of membranes composed of organic molecules, as well as proper folding of proteins. When one observes the interaction between known biopolymers and water, the impression is that water is uniquely suited as a solvent for biology.

This impression is, however, based on an intrinsic bias. The biology that works in liquid water is the biology that we see—because water is the dominant liquid stable under terrestrial conditions. But Benner and colleagues have pointed out undesirable properties of water such as, for example, the insolubility of the reactive form of carbon dioxide and the elaborate ways life has evolved to deal with it (10).

Might then liquid hydrocarbons, stable under Titan conditions, be a suitable biosolvent? Methane and ethane have their own problems, including their non-polarity, which means that as liquids they provide no support for molecular structures that depend on interaction with the liquid for their stability. But small amounts of polar molecules might exist in the Titan seas. Furthermore, an interesting "bio"chemistry might be built around the dominance of hydrogen bonding between organic molecules immersed in the non-hydrogen-bonding ethane and methane (S. Benner, pers. comm.), and in such a biochemistry, the low temperatures and consequent slow reaction rates are not necessarily a disadvantage (J. Nott, pers. comm.). While nothing like a complete, theoretical biochemistry in liquid methane and ethane has been constructed, there is no particular property or set of properties of liquid methane and ethane that could lead one to a priori rule out in such a medium a kind of self-sustaining, replicating, catalytic organic chemistry that might be called life.

Titan as a test for the ubiquity of life in the cosmos

I have deliberately not tackled the question of what constitutes life, and indeed whether it is possible to make such a definition, (11) for want of space. This makes it hard to generalize from what are regarded as the absolute requirements for life on Earth to the requirements for any chemical system we might deem worthy of being called alive. At a minimum, if we adopt organic chemistry as the basis for life, the requirements might be a fluid environment, a source of free energy and abundant organic molecules—all of which Titan possesses (12). But it is a great leap to go from terrestrial biology, with its water-based organic chemistry at room temperature, to the cold, hydrocarbon-soaked poles of Titan.

And that is precisely my point. Were one to sample the hydrocarbon lakes and seas of Titan and find structures or patterns in the organics present there that suggest chemical cycles which generate their own catalysts, or information-carrying molecules that reliably generate the same catalysts and structures over and over again, one might conclude that a second form of life had been found. And because it was found in a solvent medium completely alien—inhospitable—to terrestrial life, one could confidently conclude that it had a separate origin from life on Earth. Although Titan, like Europa, receives debris from hypervelocity impacts on Earth (13), any contaminating terrestrial life form, introduced by such impacts, would not survive the cryogenic hydrocarbon lakes of Titan. This eliminates planetary-protection concerns that plague plans for the exploration of Europa and Mars. Furthermore, life based on covalent bonds (us) and life based on hydrogen-bonding (not us) are so chemically different that the former cannot be the ancestor of the latter. Thus, even the most primitive kind of self-organizing organic chemistry in the lakes of Titan—an early step on the road to life—would be a momentous find. It would tell us immediately, with no further analysis, that life began independently multiple times in our solar system.

Titan as a model for the most common “habitable planet”

The conclusion of the previous section was admittedly provocative—but only because we know of only one kind of life, that which exists in liquid water on a planet orbiting 1 astronomical unit (150 million miles) from a so-called G-dwarf star, our Sun. Since we do not know how life formed on the Earth, we cannot extrapolate what we know of terrestrial biochemistry to other environments. But we can explore other environments, and in the next section I will argue that Titan is particularly easy to explore. But if Titan is a special case, is it really worth exploring? Does it really inform us about the fraction of planets that are habitable?

The most common type of stable star in the cosmos is not the G-dwarf—a star like the Sun—but the much less massive “M”, or red dwarf. M dwarfs are long-lived and, because they range from 1/10 to ½ the mass of the Sun, are much less luminous than our home star. A typical M dwarf is so much less bright than the Sun (14) that a planet with stable liquid water on its surface would have to orbit roughly 0.1 AU from the brightest M dwarfs—ten times closer than the Earth is to the Sun. Many large planets have been found around other stars at such close orbital distances (indeed they are easier to detect with current techniques), and so it would seem there should be no problem with imagining a plenitude of Earth-like habitable worlds in tight orbits around the universe’s most common type of star.

However, the close proximity (0.1 AU and inward) of a planet to an M dwarf raises a host of problems. Such planets are tidally locked to their parent star, presenting only one face to the source of free energy needed for life, are exposed to intense flares and stellar winds leading to loss of atmosphere (15), and may lack an amount of water sufficient to sustain a hydrosphere by virtue of having formed so close to the star (16). Whether these effects rule out life is unknown, but they certainly create complications in trying to use a simple definition of orbital distance to define a habitable, Earth-like environment—one on whose surface liquid water is stable—around M dwarfs. An Earth-sized body, even with adequate water, orbiting at 0.1 AU from an M dwarf will *not* have an environment resembling that on our home world.

Conditions at 1 AU—the Earth-Sun distance—from an M dwarf are much less severe and hence more favorable for a stable environment on a planet. A planet at 1 AU from an M dwarf can rotate decoupled from its orbital motion, as does the Earth, smoothing out the flux of light from the parent star. Flares and stellar winds at 1 AU from an M dwarf would present no more threat to a putative planet than we face from the comparable phenomena emitted from the Sun.

Because M dwarfs are so much less bright than the Sun, the same physics that dictates a world with stable liquid water must be only 0.1 AU from an M dwarf parent says that at 1 AU from such a star a planet like Titan should be present: at that distance the light from the red dwarf is so faint as to maintain liquid methane and ethane on a planet's surface, but not liquid water. And because M dwarfs outnumber G-dwarfs by a factor of between ten and a hundred, one can conclude that this situation—a Titan-like world at 1 AU—may be far and away the more common cosmic situation than our own.[1]

Therefore the search for an exotic, even if very primitive, form of life in the hydrocarbon lakes and seas of Titan has potentially profound implications for the cosmic ubiquity of life. A positive answer would force the definition of the habitable zone to be radically rewritten to include the kind of environment present on Titan.

Future exploration of the Titan environment

Titan's great distance from the Earth is its only disadvantage when it comes to exploration. Everything else about Titan: its low gravity, dense atmosphere, calm low altitude winds, low radiation levels—are distinct advantages over other solar system targets of interest for life. A robotic probe deployed by the European Space Agency successfully entered the atmosphere, descended, and landed on Titan's surface in 2005, returning data from the air and the surface (17). Replicating this mission in the high northern latitudes, in one of the great seas of Titan, with a probe instrumented to detect life, is eminently feasible even within the context of the Discovery program (18). To

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[1] The fact that Titan is a moon of Saturn is largely immaterial to the nature of its surface environment. Were Titan orbiting the Sun at Saturn's distance, it would possess essentially the same surface and atmospheric properties, being little affected by Saturn itself. However, a planet formed around an M dwarf at 1 AU would not necessarily have a mass close to that of Titan—it could have the mass of the Earth, or it could be a giant planet like Saturn or Jupiter. An Earth-mass body at 1 AU from an M dwarf could have very different surface properties from Titan, because the contribution of geothermal energy to surface heating will become significant. Under such conditions the surface might be too warm for liquid methane and ethane, but still too cold for liquid water. This would necessitate considering somewhat greater distances than 1 AU as suitable for strictly Titan-like conditions on an Earth-mass planet—but only slightly so. And that such a planet in the epoch of its formation could garner sufficient methane from a primordial disk around an M dwarf to create large-scale lakes and seas is only a plausible supposition. I do not mean to minimize such complications, but their proper treatment would require a treatise vastly longer than this work.

cover large areas of Titan's diverse surface, a more ambitious hot air balloon whose buoyancy is maintained by the waste heat of the vehicle's power source has been carefully studied by US and European space agencies (19), and by private entrepreneurs such as Julian Nott; it would be a kind of floating rover taking full advantage of Titan's dense atmosphere and benign environment.

Designing experiments to detect life in an alien environment constitutes a rich field of research unto itself (20). It is sufficient here to point out that a series of elemental, chemical and isotopic tests, coupled with an imaging microscope to examine the lake material, would be required to assess whether organic chemistry in the methane-ethane medium is being mediated in a sophisticated way indicative of life (21). At the same time, given the difficulty in searching for terrestrial-type life in exotic environments, the challenge of finding an exotic form of life in an alien environment cannot be minimized.

Conclusion

Titan has been ranked by a minority of astrobiologists as the highest priority place to go search for life in our solar system, both for the potential to find exotic life that inarguably had an independent origin from us, and the relative ease of operation on Titan's surface. I have recapitulated these arguments and added what I believe is a novel one, namely that planetary environments somewhat like Titan's may be far more common than Earth-like environments in the cosmos. This argument hinges on three points: (i) M dwarfs are the most common stable (hydrogen-burning) star in the cosmos; (ii) Earth-like temperatures on a planetary surface are achievable only in very close proximity to an M-dwarf, where the tidal and energetic environment would create decidedly non-Earthlike, and possibly unstable, environments; (iii) a Titan-like planetary environment is achieved at orbital distances from an M-dwarf which are comparable to the Earth-Sun distance, and where conditions should be stable.

The dichotomy I have laid out here between Earth-like and Titan-like planets is an obvious oversimplification: one might imagine a diversity of planets around M dwarfs including those that are Europa-like, Mars-like, or for which no solar system analog exists whatsoever. And all potential life-sustaining environments available for study in our solar system should be searched. But of these *only Titan provides both easy accessibility to the potential habitable environment of interest and an assurance that—should life be found—its origin is independent from that of life on Earth.*

Saturn's moon Titan, therefore, should be a prime target in the search for life. Should the methane-ethane seas of Titan host an exotic form of life not based on the same biochemistry as that in water on the Earth, or even "merely" a kind of self-replicating, autocatalytic chemistry not achievable in terrestrial laboratories, the question of whether life is or is not a common cosmic phenomenon will have been largely answered.

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