DRAGONFLY AND THE EXPLORATION OF TITAN'S ASTROBIOLOGICAL POTENTIAL. K. P. Hand[1], E. P. Turtle[2], J. W. Barnes[3], R. D. Lorenz[2], S. M. MacKenzie[2], M. L. Cable[1], C. D. Neish[8], M. G. Trainer[4], E. R. Stofan[2], C. Freissinet[5], S. M. Horst[6], C. P. McKay[7] J. M. Lora[9], J. Radebaugh[10], A. G. Hayes[11], [1]Jet Propulsion Lab., Pasadena, CA (khand@jpl.nasa.gov) [2]Johns Hopkins Applied Physics Lab., Laurel, MD, [3]Univ. Idaho, Moscow, ID, [4]NASA Goddard Space Flight Center, Greenbelt, MD, [5]Laboratoire Atmosphères, Milieux, Observations Spatiales, Guyancourt, France, [6]Johns Hopkins Univ., Baltimore, MD, [7]NASA Ames Research Center, Moffett Field, CA, [8]Planetary Science Institute, Tucson, AZ, [9]Univ. California, Los Angeles, CA., [10]Brigham Young Univ., Provo, UT, [11]Cornell Univ., Ithaca, NY.

Titan in the Context of Astrobiology: Titan is the carbon world of our solar system. The combination of carbon, water, and dynamic physical and chemical processes make Titan a prime target for astrobiology, both for life as we know it (water-solvent-based), and for life as we do not know it ('weird life'). Considering the potential for life as we know it, two metrics are critical: 1) assessing the conditions needed for life to originate, and 2) assessing the conditions needed for habitability, past and present.

On Origins: Pathways for the origin of life are poorly constrained, however there is general agreement that liquid water, a suite of essential elements (most significantly CHNOPS), some form of energetic disequilibrium, and a catalytic surface are all required. On early Earth, the proposed locales for combining these ingredients are highly varied – from deep-sea hydrothermal vents to tidal pools on the shores of an ancient sea. ***Significantly, Titan is one of only four worlds in our solar system where both the ingredients AND the variety of locales for origins would have converged*** (Earth, Mars, and possibly Venus being the others). Titan's subsurface ocean may have hosted (and may continue to host) hydrothermal activity, and its ice shell may have hosted chemically-rich evaporitic and/or freeze-desiccating environments, especially around silicate-containing impact material. Unlike tidal pools on the Earth, which were dominated by liquid water, impact pools on Titan would have had transient liquid water, sustainable for ~10^3-10^6 years [1-3]. If the origin of life requires an evaporitic environment, such as impact pools or even seasonal rivers [4], in contact with a photochemically active atmosphere, then life could have emerged on a young Titan surface and subsequently adapted and migrated to the subsurface, where conditions may have provided a long term habitable environment. Significantly for life's origins, Titan's cold temperatures and the limited availability of liquid water near the surface could enhance the stability of large, complex organic compounds while also limiting hydrolysis from an excess of water (a known problem for the emergence of life on Earth). Furthermore, while cold temperatures limit reactivity, metabolisms scale accordingly – thus leading to lower power demands for driving early life.

On Habitability: Titan in the modern epoch may be habitable in the subsurface (ocean, liquid-water pockets), but its surface is too cold to sustain life that utilizes liquid water as its dominant solvent. With regard to seeking potential biosignatures, Titan then poses two interesting scenarios: 1) searching for signs of extant life as delivered from subsurface habitable environments via crustal exchange process, and 2) searching for signs of past life from epochs when liquid water-based life may have been transiently sustainable on the surface. In the first case, Titan is perhaps similar to Europa, Enceladus, and possibly even Ganymede in that the ice shells may serve as windows (albeit imperfect windows) into the subsurface liquid water regions.

In the second case, the search for potential biosignatures on Titan is perhaps analogous to our efforts on Mars, where on that world planetary-scale surface habitability diminished significantly around 3.0-3.5 Gya. Thermal-orbital models [5] suggest Titan's crust thickened from a few km to >50 km at ~0.3-1.2 Ga, which is consistent with observations of the crater retention age of 0.2-1 Gyr [6]. During the first ~ 3 Gyr of Titan's history the ice shell may have been relatively thin (<10 km) and dominated by methane clathrates [5]. In other words, were life to have originated on Titan's surface or within Titan's interior, exchange between the surface and subsurface may have been considerably easier >0.5 Ga. Life that originated on the surface could have adapted and sought refuge in the subsurface, and life that originated in the ocean may have been brought to the surface through fractures and plumes. Organics from that epoch of thinner ice may reveal the extent of hydrocarbon chemistry in the ocean, and any biosignatures. Differentiating endogenous ocean-derived organics from photochemically produced tholins requires sampling of the surface to determine organic complexity [7], as well as any association with oceanic compounds, such as salts. One of the most concentrated sediments on Titan are the evaporites, which line many of Titan's lakes and empty lakebeds [8, 9]. Their spectra suggest they are organic, but the exact composition is unknown [10]. Experiments on hydrocarbon evaporitic process have shown formation of ethane and benzene co-crystals, forming a material akin to a hydrated salt on Earth, which could also serve to selectively sequester hydrocarbons [11-

13]. As a result, shoreline evaporitic deposits may present a natural separation of organic materials that help elucidate the origin and history of organics on Titan.

For persistent habitability, and habitability into the modern epoch, perhaps the most uncertain of Titan's parameters is the availability of metabolically useful redox pairs needed to power life. Titan is awash with reductants, but may be oxidant limited. Proposed metabolisms include organics such as ethane and acetylene as the electron acceptor (oxidant), with hydrogen being the reductant [14]. Decay of radiogenic nuclides in the ice shell, similar to that proposed for Europa [15], could provide a limited but useful source of O_2, H_2O_2, hydroxides and other oxidants.

On life as we do not know it: Although the possibilities of living processes in non-aqueous solvents have not been fully explored, some ideas specific to Titan conditions have been suggested. McKay and Smith (2005) have proposed that hydrogen-acetylene reactions in the surface could provide available free energy [14]. Others have noted that the available acrylonitrile could form 'azotosomes', an analog for liposomes, forming vesicles in liquid hydrocarbon environments [16]. Also of significance, as mentioned above, is that Titan's lakes and seas have tides due to Saturn, and so cyclic concentration and remixing may occur. Periodic desiccation of the seas may also occur due to astronomical (~30,000-yr and 10^3-10^4 yr Croll-Milankovich) climate cycles [9, 17, 18, 30]. Such events may allow prebiotic or biological matter to be exposed and redistributed by aeolian processes.

Dragonfly and Astrobiology: The *Dragonfly* mission would explore Titan's surface to address fundamental questions regarding organic chemistry, habitability, and the search for potential biosignatures. Direct sampling of the surface by *Dragonfly* would elucidate the complexity of Titan's surface organics to assess the extent of prebiotic chemistry and any biosignatures [19]. Life still lacks a universal definition [20], but operationally life on Earth exhibits common chemical characteristics [7, 21]. Evaluating the relative abundance and distribution of organics is diagnostic for biology that uses liquid water as a solvent, as well as biology that might use liquid hydrocarbons [7, 21]. A broad-based search for multiple chemical biosignatures minimizes assumptions about the nature of any potential life, a valuable lesson from *Viking* experiments [22-24]. This robust strategy draws from the astrobiology 'Life Detection Ladder' and from other missions chartered to search for potential biosignatures [25-27].

The *Dragonfly* mission would also constrain dominant transport processes, active transport rates, and sources of material in the equatorial region, serving to improve our understanding of if and how Titan's habitability is controlled by the transport and availability of organic material. Furthermore, *Dragonfly* would identify and constrain surface and subsurface exchange processes, serving to elucidate mechanisms that permit liquid water to mix with organic compounds

The mobility of the *Dragonfly* rotorcraft lander would allow us to address all of these aspects of Titan in a complete, integrated scientific investigation. The initial landing site in an interdune flat provides access to materials with a water-ice component, as well as Titan's vast sediment sink of organic sand, which may represent a principal end product of Titan's organic chemistry [28, 29]. Further exploration, including potential targets with potential past liquid water exposure, would provide comparison of chemistry in different environments. Geophysical studies will provide constraints on Titan's interior structure and ocean-surface exchange processes.

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