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Science Goals and Objectives for the Dragonfly Titan Rotorcraft Relocatable Lander

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Abstract

NASA's Dragonfly mission will send a rotorcraft lander to the surface of Titan in the mid-2030s. Dragonfly's science themes include investigation of Titan's prebiotic chemistry, habitability, and potential chemical biosignatures from both water-based "life as we know it" (as might occur in the interior mantle ocean, potential cryovolcanic flows, and/or impact melt deposits) and potential "life, but not as we know it" that might use liquid hydrocarbons as a solvent (within Titan's lakes, seas, and/or aquifers). Consideration of both of these solvents simultaneously led to our initial landing site in Titan's equatorial dunes and interdunes to sample organic sediments and water ice, respectively. Ultimately, Dragonfly's traverse target is the 80 km diameter Selk Crater, at 7° N, where we seek previously liquid water that has mixed with surface organics. Our science goals include determining how far prebiotic chemistry has progressed on Titan and what molecules and elements might be available for such chemistry. We will also determine the role of Titan's tropical deserts in the global methane cycle. We will investigate the processes and processing rates that modify Titan's surface geology and constrain how and where organics and liquid water can mix on and within Titan. Importantly, we will search for chemical biosignatures indicative of past or extant biological processes. As such, Dragonfly, along with Perseverance, is the first NASA mission to explicitly incorporate the search for signs of life into its mission goals since the Viking landers in 1976.

Unified Astronomy Thesaurus concepts: Titan (2186); Pre-biotic astrochemistry (2079); Astrobiology (74); Planetary atmospheres (1244); Planetary surfaces (2113)

1. Introduction

One of the most important discoveries from the last 20 years of planetary exploration has been the astrobiological potential of icy moons. Many of these moons harbor liquid-water reservoirs beneath their crusts, comprising a new class of solar system body: ocean worlds (e.g., Nimmo & Pappalardo 2016). If biology requires carbon, water, and energy, then ocean worlds may offer the solar system's best chance for life beyond Earth (Chyba & Hand 2005; Lazcano & Hand 2012; McKay 2016; Lunine 2017; Hendrix et al. 2019; Hand et al. 2020).

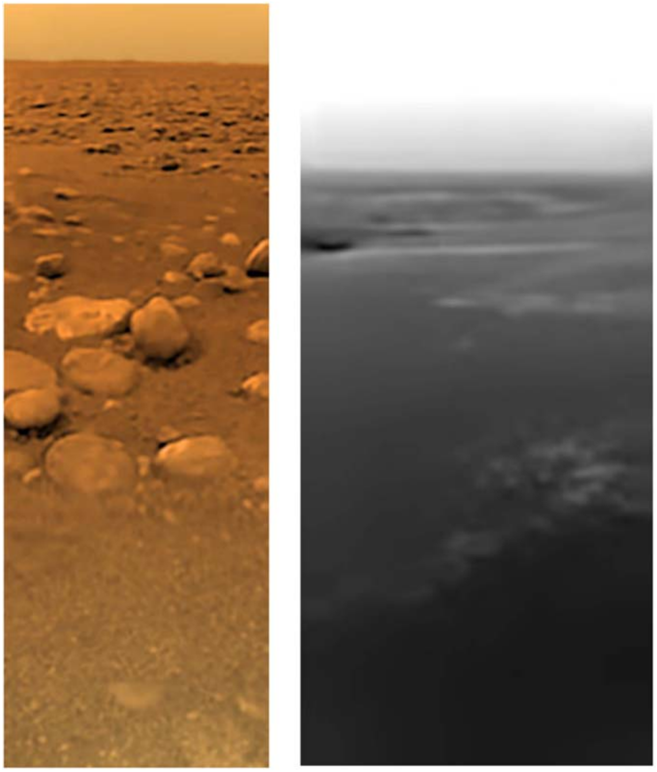

Figure 1. Dragonfly will image from the surface to provide context for sampling and measurements, as well as in flight to identify sites of interest at a variety of locations. (Left) Huygens image of Titan's surface; cobbles are 10–15 cm across and may be water ice (Tomasko et al. 2005; Keller et al. 2008; Karkoschka & Schröder 2016a). (Right) Huygens aerial view of terrain akin to the diverse equatorial landscapes that Dragonfly will traverse and image at higher resolution.

Titan is unique among ocean worlds in that carbon, water, and energy interact *on the surface* (Figure 1). Complex, potentially tholin-like organic compounds cover most of the surface (Janssen et al. 2016). Crustal ice (Coustenis 1997; Griffith et al. 2003) can be melted by impacts (Artemieva & Lunine 2003), and liquid water from the subsurface ocean may erupt in cryovolcanic flows (Lopes et al. 2013). Solar (photolytic) and chemical energy could power biochemistry (Raulin et al. 2010). Titan's profusion of organic riches, especially when exposed to transient liquid water, has created potentially habitable environments, the remnants of which are available on Titan's surface today.

Dragonfly will explore some of these environments to address fundamental questions regarding prebiotic chemistry, habitability, and the search for biosignatures. The vehicle is a single half-ton X8 octocopter. We think of it as a rotorcraft relocatable lander: we spend nearly all of our time on the ground doing science and uplinking data, only flying for around half an hour to a new landing site once every 2 Titan days (32 Earth days). Dragonfly's targeted landing site is near Titan's equator, 700 km north of Huygens, in the Shangri-La sand sea and within traverse distance of Selk impact crater (Lorenz et al. 2021). Our prime mission will take place during northern hemisphere winter. We include a brief description of Dragonfly's science payload in Table 1, and see also Lorenz et al. (2018b) for further description of the Dragonfly mission concept.

While Lorenz et al. (2018b) described the mission implementation, here we provide a complementary focus on the science goals and objectives of the mission. Section 2 describes prebiotic chemistry. Section 3 addresses habitability in both liquid water and liquid hydrocarbon solvents, including mission goals related to the methane cycle, surface geology, and geophysics. We discuss Dragonfly's search for chemical biosignatures in Section 4. We then specify Dragonfly's landing site and traverse strategy as it relates to science in Section 5, before concluding in Section 6.

2. Prebiotic Chemistry

Titan is a carbon- and nitrogen-rich natural laboratory for prebiotic chemistry. No Earth-based experiment can reproduce the long time periods over which appropriate conditions existed prior to the formation of terrestrial life. However, we can investigate analogous conditions on Titan, thereby empirically constraining the degree of molecular complexity that can be achieved with prebiotic chemistry.

Titan's dense atmosphere of nitrogen and methane supports rich organic photochemistry. Radiolysis and ultraviolet (UV) photolysis dissociate atmospheric components to produce a suite of carbon–hydrogen–nitrogen ($C_xH_yN_z$) compounds. Voyager observed these products in Titan's atmosphere (Hanel et al. 1981; Kunde et al. 1981; Maguire et al. 1981), and Cassini-Huygens and Earth-based observations have shown organics to be diverse and bounteous in the atmosphere and on the surface (Niemann et al. 2005; Cordiner et al. 2015, 2018; Janssen et al. 2016; Hörst 2017; Lai et al. 2017; Thelen et al. 2019, 2020; Nixon et al. 2020). Surface detections have been limited to the relatively simple species CH_4, C_2H_2, CO_2, C_2N_2, C_6H_6, C_2H_6, and HC_3N (Barnes et al. 2005; Niemann et al. 2005, 2010; Brown et al. 2008; McCord et al. 2008; Clark et al. 2010; Mastrogiuseppe et al. 2014). However, Cassini observed the production of more exotic species in the upper atmosphere, including propane, butane, and polycyclic aromatic hydrocarbons (PAHs; Waite et al. 2007; Cui et al. 2009; Magee et al. 2009; Dinelli et al. 2013; López-Puertas et al. 2013). Even larger and more complex atmospheric molecules, with molecular weights of thousands of Daltons (Da), have been detected but not resolved (Coates et al. 2007, 2009; Waite et al. 2007) due to instrument limitations. These atmospherically produced organics coalesce into haze particles that then settle out to cover much of Titan's water-ice bedrock (Rodriguez et al. 2006; Barnes et al. 2007a; Soderblom et al. 2007; Le Mouélic et al. 2008; Janssen et al. 2009, 2016; Hayne et al. 2014; Neish et al. 2015; Lopes et al. 2019).

But at what point does organic chemistry become prebiotic chemistry? It has long been hypothesized that Earth's prebiotic chemistry could have been initiated via atmospheric synthesis (Miller & Urey 1959; Trainer 2013; Rapf & Vaida 2016). Organic haze, like that on Titan today, may have played an integral role in the development of Earth's earliest biosphere (Trainer et al. 2004, 2006; Arney et al. 2016). On Earth, the transition from organic to prebiotic chemistry may have occurred as photochemically generated organics mixed into the primitive water ocean. On Titan, surface liquid water, e.g., impact melt, could potentially play the same astrobiological role as Earth's early oceans, providing an environment for the organic haze products that accumulate on Titan's surface to progress toward more complex molecules, possibly with biological potential (Neish et al. 2010, 2018). Laboratory experiments show that Titan haze analogs produce biological molecules, such as amino acids, when mixed with liquid water (Neish et al. 2008, 2009, 2010; Ramírez et al. 2010; Poch et al. 2012; Cleaves et al. 2014). Reactions occurring on Titan in

Table 1
Dragonfly's Science Instruments

Name	Acronym Expansion	Description
DraMS	Dragonfly Mass Spectrometer	Derived from SAM on Curiosity and MOMA on ExoMars, DraMS is a linear ion trap mass spectrometer that operates in three modes (laser desorption, gas chromatography, and atmospheric enrichment) to measure the mass of molecules up to ∼2000 Daltons in surface and atmospheric samples (Trainer et al. 2018).
DraGNS	Dragonfly Gamma-Ray and Neutron Spectrometer	Using a pulsed neutron generator, DraGNS interrogates Titan within 2 m of the lander to measure bulk elemental composition in the shallow subsurface, particularly C, H, N, O, Na, Mg, P, S, Cl, and K (Parsons et al. 2018; Peplowski et al. 2021).
DraGMet	Dragonfly Geophysics and Meteorology package	DraGMet is an extensive set of instruments measuring 11 distinct properties: atmospheric temperature, pressure, wind speed and direction, methane humidity, hydrogen partial pressure, crustal seismicity, electric field, surface dielectric properties, surface temperature, and ambient sound (Lorenz et al. 2018a, 2019; Panning et al. 2020).
DragonCam	Dragonfly Camera suite	Dragonfly carries eight scientific cameras: two panorama cameras attached to the high-gain antenna for pointing, two fixed forward-looking cameras, two wide-angle downward-looking workspace cameras boresighted on the left and right sampling sites, and two microscopic cameras with 60 μm pixels focused on the samples to be ingested (Turtle & the Dragonfly Science Team 2018).
(DrACO)	Drill for Acquisition of Complex Organics	Though not technically a science instrument, DrACO drills into Titan's surface and vacuums up samples of surface materials, delivering them into DraMS at cryogenic temperature (Zacny et al. 2019; Bar-Cohen & Zacny 2020; Zacny et al. 2020).

Note. See Lorenz et al. (2018b) for additional details.

transient liquid-water environments provide a natural experiment in the transition from organic to prebiotic to biological chemistry, perhaps paralleling the transition on early Earth. Titan has been conducting such experiments over millions of years; Dragonfly is designed to collect the results.

2.1. Goal A: Prebiotic Chemistry

Science question: What chemical components and energy-producing chemical pathways exist on Titan that could drive prebiotic chemistry?—Complex $C_xH_yN_z$ molecules, the main ingredients for prebiotic chemistry, are abundant on Titan's surface, where they have the potential for further chemical evolution when dissolved in a solvent (Neish et al. 2010; Rahm et al. 2016). However, it is not known how far organic synthesis has progressed in complexity and whether abiotic processes have produced chemical gradients that might be utilized by organisms. Designed primarily as an atmospheric probe, Huygens could not conduct a full inventory of Titan's surface organics. Identification of a full suite of organics, including those most relevant to biology, requires a dedicated surface mission. Dragonfly will document the complexity of Titan's surface organics to assess the extent of prebiotic chemistry in a carbon-rich environment. *Science goal A:* determine the inventory of prebiotically relevant organic and inorganic molecules and reactions on Titan.

2.1.1. Science Objective A1: Measure Compositions of Materials in Different Geologic Settings

Elemental availability—Dragonfly will sample Titan's organic sediments to determine the abundance and distribution of carbon, hydrogen, nitrogen, oxygen, and possibly phosphorous and sulfur (known collectively as CHNOPS). Known biological processes preferentially use these specific elements, but not all CHNOPS-bearing species are biochemically useful (Bains & Seager 2012). Identifying the relative abundance and oxidation states of precursors like hydrogen cyanide (HCN), hydrogen sulfide (H_2S), and formaldehyde (CH_2O; Miller 1957; Oró & Kimball 1961; Orgel 2004) will reveal how CHNOPS might build functional molecules on Titan.

The elements C, H, and N are known to exist on Titan's surface, but the case for chemically accessible O, P, and S is less clear. A small amount of oxygen is incorporated into organics in the upper atmosphere (Lutz et al. 1983; Samuelson et al. 1983; Coustenis et al. 1998; Baines et al. 2005; de Kok et al. 2007; Hörst et al. 2012), ultimately derived from exogenic water arriving at Titan from Saturn's E-ring (Hörst et al. 2008). However, a larger amount of oxygen could easily be incorporated into Titan's surface organics through reactions with liquid water to produce a range of biomolecules (Neish et al. 2008, 2009, 2010; Poch et al. 2012; Cleaves et al. 2014). Such reactions are likely to occur in melt produced by impacts and could potentially occur in cryovolcanic flows, although impacts produce higher-temperature melt that would persist for longer durations than individual flows (Neish et al. 2018). P and S are present at most at the part-per-billion level in Titan's stratosphere but are expected based on relative abundance in the Saturn system (Nixon et al. 2013) and could be delivered to the surface through other means (Fortes et al. 2007; Pasek et al. 2011).

2.1.2. Science Objective A2: Determine Presence and Abundance of Key Molecules for Earth-like Life

Building blocks—Dragonfly will also look for biologically relevant compounds—amino acids, lipids, and sugars—and their precursors. Terrestrial biology uses amino acids to build proteins that form cell structures and catalyze reactions. They range in size from 75 Da (glycine; $C_2H_5NO_2$) to more than 204 Da (tryptophan; $C_{11}H_{12}N_2O_2$). Amino acids can form abiotically and have been detected in meteorites (Kvenvolden et al. 1970), on comets (Elsila et al. 2009), and in interstellar space (Kuan et al. 2003). They are also produced with ease in Titan analog laboratory experiments (Neish et al. 2010; Poch et al. 2012; Cleaves et al. 2014). Dragonfly will identify the abundance,

Table 2
Free Energies of Hydrogenation for Some Possible Titan Reactions

Reaction	ΔG (kJ mole^{-1})	Citation
$C_2H_2 + 3H_2 \rightleftharpoons 2CH_4$	−334	McKay & Smith (2005)
$C_2H_6 + H_2 \rightleftharpoons 2CH_4$	−62.8	McKay & Smith (2005)
$R\text{-}CH_2 + H_2 \rightleftharpoons R + CH_4$	−54.4	McKay & Smith (2005)
$R\text{-}NH_2 + CO_2 \rightleftharpoons R\text{-}NH\text{-}COOH$	<0	Hodyss et al. (2015)

variety, and spatial distribution of amino acids within Titan's surface materials, allowing us to map out the degree to which prebiotic chemistry has progressed.

Dragonfly will also identify sugars and lipids. More than just an energy source, sugars also form the backbone of RNA (ribose; $C_2H_{10}O_5$) and DNA (deoxyribose; $C_5H_{10}O_4$). One idea for the formation of life on Earth posits that RNA was first produced abiotically, after which it gained the ability to self-replicate and manipulate its environment (Woese 1967; Crick 1968; Orgel 1968, 2003; Gilbert 1986; Robertson & Joyce 2012; Neveu et al. 2013). By identifying sugars on Titan, we can assay the possible inputs for building RNA and/or potential alternate biomolecules. Lipids (e.g., fatty acids) are organic molecules that terrestrial life uses to build structures, such as membranes and cell walls needed to isolate cells from their environment. Isolation may not even require oxygen; Stevenson et al. (2015) suggested that an azotosome might serve for isolation in liquid hydrocarbons. Identifying simple forms of lipids (e.g., $C_{16}\,H_{30}O_2$; 254 Da) on Titan would reveal the potential for compartmentalization.

Energy-producing pathways—Although a thousand times less intense than at the surface of the Earth (Barnes et al. 2018), the best continuous source of energy on Titan is still sunlight (McKay 2016). However, transient habitable environments or opportunistic biota might alternatively derive metabolic energy from chemistry alone, similar to chemosynthesis-driven systems found near seafloor hydrothermal vents on Earth (Corliss et al. 1979; Kelley et al. 2005). Potential hydrocarbon-based life might derive energy chemically from hydrogenation of hydrocarbons on Titan's surface (McKay 2016). For example, acetylene (C_2H_2) could react with hydrogen gas (0.1% of Titan's atmosphere) to generate 334 kJ mole^{-1} (McKay 2016; Table 2). We will constrain the potential energy that could be derived from this and other chemical reactions common enough to be biologically useful by inventorying abundant compounds. In addition to the hydrogenation of acetylene, Table 2 lists other examples of reactions thought to be common or biologically useful on Titan's surface. To be most useful, target molecules will occur in abundance; so, based on Titan's upper atmospheric chemistry, they will likely be relatively simple (20–100 Da).

2.1.3. Sampling Targets for Goal A

Dragonfly will measure concentrations of chemical constituents in organic dune sands (α) and material with a water-ice component (β, γ, or δ; Table 3). Comparison of these materials can show how far prebiotic chemistry can progress in different environments. For example, mixing of organics with transient liquid water on Titan's surface could advance chemistry by offering a solvent in which chemical reactions can occur, increasing reaction rates, and allowing for incorporation of oxygen into Titan's organic inventory (Neish et al. 2008, 2009, 2018).

3. Habitability

An environment's habitability depends on conditions including the abundance and distribution of chemical nutrients, as well as potential solvents. Titan's surface hosts two possible liquid solvents: water and methane. Although the surface temperature is 93.6 ± 0.2 K (Fulchignoni et al. 2005; Lebreton et al. 2009; Jennings et al. 2019), transient oases of liquid water have existed, for example, in melt generated in impact events (Artemieva & Lunine 2003; Section 5).

Methane plays a role on Titan analogous to that of water on Earth, so Titan's hydrologic cycle provides a unique opportunity to study familiar processes under very different conditions. Methane rainstorms (Griffith et al. 2005; Turtle et al. 2011a, 2011b) and runoff carve fluvial channels (Tomasko et al. 2005). Lakes and seas (Stofan et al. 2007; Hayes 2016), subsurface reservoirs (Stofan et al. 2007; Birch et al. 2017; Turtle et al. 2018), and atmospheric methane interact via evaporation, precipitation, and surface/subsurface transport (Hayes et al. 2008, 2018; Horvath et al. 2016; Mitchell & Lora 2016; Faulk et al. 2019; MacKenzie et al. 2019).

On Titan, methane acts both as a source of carbon and as a solvent. The equatorial regions provide ample organic solids (e.g., dune sands). And, although rainfall is infrequent, the regolith may serve as a liquid-methane reservoir in the near subsurface (Zarnecki et al. 2005; Lorenz et al. 2006a; Hayes et al. 2008; Niemann et al. 2010; Lorenz 2014; Turtle et al. 2018; Faulk et al. 2019). The persistence of liquid methane, the rate of introduction of organic solids and their concentration by evaporation, and the prospects for mixing of organics with liquid water at, near, or below the surface determine the timescales and abundances with which biochemistry can operate, thus defining Titan's habitability.

3.1. Goal B: Methane Cycle

Science question: What methane sources and sinks exist in Titan's equatorial regions, and what are the implications for methane transport?—By influencing the spatial and temporal availability of organic material and hydrocarbon solvents, Titan's methane cycle drives its potential as a habitable world. Cycles operate on two timescales: a faster, closed hydrologic cycle of methane precipitation, transport, and evaporation (Mitchell & Lora 2016) and a slower, open cycle of methane production, loss, and potential resupply from the interior (Tobie et al. 2006). Both affect the capacity for prebiotic chemistry. Dragonfly will constrain Titan's methane cycle and conditions for habitability by recording atmospheric and shallow subsurface conditions in the equatorial regions to tie to global atmospheric circulation and the history of atmospheric methane. *Science goal B*: determine the role of Titan's tropical atmosphere and shallow subsurface reservoirs in the global methane cycle.

3.1.1. Science Objective B1: Constrain the Atmospheric Methane Moisture Budget

Dragonfly meteorological measurements will be used to derive constraints on Titan's equatorial moisture budget (Mitchell 2008; Mitchell & Lora 2016) to anchor models of the global hydrologic cycle. Despite periodic rainfall

Table 3
Geologic Units and Compositional Tests to Determine Provenance

	Material	Chemical Test	DraMS	DraGNS	Hypothesis to Be Evaluated
α	Dark dune sand	Oxygen > 1%	•	•	Dune sands contain ice/crustal material
		Nitrogen < 5%	•	•	Sand chemically altered from tholin haze or different synthesis, e.g., shock versus photochemistry
		Ethane > 10%	•		Haze/sand as ethane sink, "smust" (Hunten 2006)
		Acetylene > 1%	•		Abiotic hydrogen sink; McKay & Smith (2005) predicted "complete consumption" of C_2H_2 by methanogenic metabolism
β	Interdune gravels, crustal material	N > 5%, C < 20%	•	•	Crustal material contains ammonia; would suggest deposition as cryolava[a]
		Na, K, Mg present		•	Dissolved salts; rocky core interacted with liquid water, deposited on surface as cryolava[a]
		S present		•	Dissolved sulfate; would favor ocean model predicting chondritic sulfur deposition early in Titan's history and subsequent sulfate dissolution in ocean (Fortes et al. 2007)
γ	Ejecta blanket	Amino acids	•		Shock synthesis in vapor cloud; mixing of organics with melt entrained in the ejecta blanket
		Relatively pure H_2O	•	•	Vapor deposition (Le Mouélic et al. 2008)
δ	Impact melt	Nitrogen ~26%	•	•	Water–ammonia peritectic composition indicates material froze last
		Amino acids	•		Amino acid indicates formation by tholin hydrolysis (Neish et al. 2010)

Note.
[a] A global water ocean, cooled from above, would drain solute-rich liquid to the ocean, leaving surface ice relatively pure. The surface presence of solutes in ice implies deposition of liquid above the crust so solutes can be frozen in.

(Griffith et al. 2005; Schaller et al. 2009; Turtle et al. 2011a, 2011b; Barnes et al. 2013) and fluvial channels (Barnes et al. 2007b; Lorenz et al. 2008b; Burr et al. 2013), the equatorial region is generally arid, consistent with global transport of volatiles toward the poles and indicative of high average potential evaporation, low atmospheric humidity, and little precipitation.

Surface–atmosphere exchange—Evaporation is controlled by wind speed, surface texture, the humidity gradient between surface and atmosphere, and atmospheric mixing, which is a function of atmospheric stability. Volatile exchange leaves a signature in the diurnal variations of near-surface temperature and humidity. To assess the potential evaporation as a function of time and location, Dragonfly will monitor methane humidity, temperature, and atmospheric winds at the surface at each site. We will use this information, along with knowledge of surface moisture and porosity (science objective B2), to model and constrain actual evaporation rates (Gloesener et al. 2016; Martínez et al. 2016; Savijärvi et al. 2016; Farris et al. 2018).

Moisture transport—To constrain local atmospheric moisture transport in the boundary layer, Dragonfly will measure methane humidity and winds. By monitoring the diurnal methane cycle and meteorology at multiple locations over the mission, which will take place within a single Titan season, we will provide constraints on regional variations in humidity and transport. While Huygens provided a snapshot of local atmospheric conditions, Dragonfly will put these measurements and ground-based observations (Lora & Ádámkovics 2017) in the context of Titan's diurnal and longer-term cycles, as well as regional weather variations. These constraints will then be used to evaluate atmospheric circulation modeling of the global methane cycle (Mitchell 2012; Lora & Mitchell 2015; Lora et al. 2015; Newman et al. 2016; Faulk et al. 2019; Tokano 2019).

Atmospheric stability and precipitation—Rainstorms are infrequent at low latitudes on Titan and are expected to be clustered near equinox (~5 yr after Dragonfly's expected arrival), so Lora et al. (2019) showed that Dragonfly is unlikely to experience rain (Lorenz 2000; Tokano et al. 2006; Schaller et al. 2009; Turtle et al. 2011b; Mitchell 2012; Lora et al. 2015; Mitchell & Lora 2016; Newman et al. 2016). Nevertheless, Dragonfly will acquire vertical atmospheric profiles of methane content and temperature, allowing us to constrain atmospheric (in)stability, characterize the cloud-base altitude and energy available for convection, and assess the likelihood and intensity of future precipitation events (Hueso & Sánchez-Lavega 2006; Barth & Rafkin 2007, 2010).

3.1.2. Science Objective B2: Abundance of Stored Liquid Methane

Dragonfly measurements will determine if Titan's near subsurface can act as a liquid reservoir for hydrocarbons in the tropics (within 26° of the equator), where precipitation is infrequent and surface liquids evaporate quickly (Mitchell 2008; Turtle et al. 2011b; Barnes et al. 2013). Huygens' detection of methane and ethane moisture in the regolith at 10° S latitude (Niemann et al. 2010) is consistent with the presence of porous water ice and organic materials, as also suggested by Cassini data (Elachi et al. 2005; Janssen et al. 2016). For infiltration to be effective, the upper crust must have a high porosity. On Earth, the void space between sand grains inside dunes acts as a water reservoir, retaining humidity levels high enough to support microbial communities beneath the surface, even in hyperarid deserts (Louge et al. 2013). Impacts have been shown to increase the near-surface porosity within and surrounding their resulting craters via fracturing and dilatancy (Pilkington & Grieve 1992; Alejano & Alonso 2005; Collins 2014), with the largest impacts creating higher porosity and to greater depths (Soderblom et al. 2015).

Dragonfly will constrain near-subsurface liquid content and porosity by measuring the electric permittivity (complex dielectric constant ϵ) and thermal diffusivity (κ in $m^2\,s^{-1}$) of the surface. Electric and thermal responses of the surface are functions of the amount of pore space and the bulk composition. Analysis of the thermal diffusivity at the Huygens GCMS inlet confirmed that the surface was damp (Lorenz et al. 2006a), and changes in the dielectric response (Hamelin et al. 2016) showed evidence of surface devolatilization minutes after Huygens landed. Although interpretation of a single physical property is not unique, Dragonfly can resolve this ambiguity by bulk elemental compositions from gamma-ray spectroscopy. Thus, we will be able to detect whether near-subsurface liquids are present and map their spatial distribution from site to site, determining how dry Titan's equatorial region is and its role in the global methane cycle.

3.1.3. Science Objective B3: History of Titan's Atmospheric Methane

Dragonfly will test different hypotheses to address outstanding questions regarding the formation and evolution of Titan's atmosphere. Despite the abundant hydrocarbons on Titan's surface, the total inventory is lower than the amount predicted if current photolytic processes have operated throughout Titan's history (Yung et al. 1984; Lorenz & Lunine 1996; Lorenz et al. 2008c). Furthermore, Cassini isotopic measurements are consistent with primordial methane, implying replenishment from the interior within the last few hundred megayears (Wilson & Atreya 2004; Lavvas et al. 2008; Mandt et al. 2012; Nixon et al. 2012). While outgassing (e.g., due to methane clathrate destabilization; Tobie et al. 2006) could have supported a long-term methane cycle, extended periods without methane might also have been possible. Such scenarios affect the carbon supply and duration of availability for prebiotic chemistry.

Dragonfly will measure Ar and Ne isotopic distributions to constrain how much outgassing has occurred in Titan's history. These elements are poorly soluble in potential subsurface clathrate reservoirs and are therefore the most likely markers of outgassing. Huygens' brief mission detected more radiogenic Ar in Titan's atmosphere than expected (Niemann et al. 2010), evidence of chemical interactions with the rocky core and interior ocean. Huygens also made a tentative detection of ^{22}Ne (Niemann et al. 2010), which, if confirmed, would suggest the release of 20–30$\times$ Titan's atmospheric mass over its history (Tobie et al. 2012). The abundance of ^{22}Ne and its isotopologs traces the evolution of Titan's atmosphere (Glein 2015, 2017).

Dragonfly will also aim to measure or place improved upper limits on the relative Xe, Kr, and Ar abundances to test the hypothesis that a significant amount of Titan's volatiles, including CH_4, could be trapped in clathrates in the interior (Mousis et al. 2011). Measurement of significant depletion among ^{132}Xe, ^{84}Kr, and ^{36}Ar compared to carbonaceous chondrites and comets, possible sources of Titan's volatiles (Néri et al. 2020), would strongly indicate retention of volatiles in clathrates rather than early outgassing and subsequent atmospheric loss as on terrestrial planets.

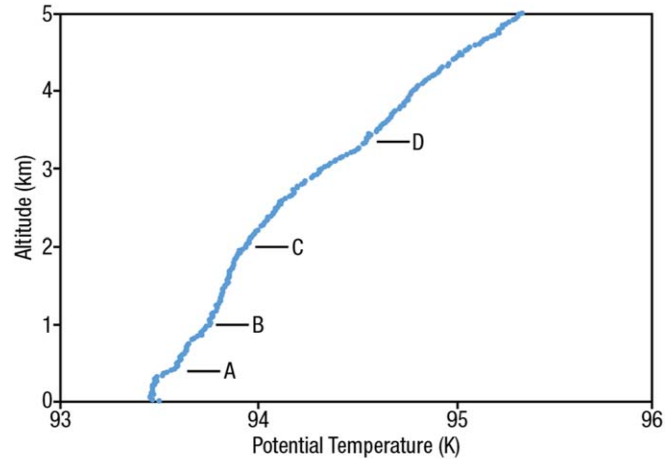

Figure 2. Huygens atmospheric profile showing boundary-layer features at a few hundred meters and 1, 2, and 3.5 km (labeled A, B, C, and D) after Lorenz et al. (2010). See also Charnay & Lebonnois (2012).

3.1.4. Sampling Targets for Goal B

Dragonfly will acquire meteorological measurements at the surface in multiple geologic settings to determine evaporation potential and atmospheric humidity in Titan's arid equatorial region in northern winter. We will fly vertical atmospheric profiles extending from the surface up to 3.5 km altitude to encompass the planetary boundary layer detected by Huygens on its descent (Lorenz et al. 2010), sampling temperature, pressure, and methane abundance at 20 m intervals to resolve the altitude of the boundary layer (Figure 2). For objective B3, DraMS will acquire atmospheric samples.

3.2. Goal C: Geologic Provenance

Science question: How are solid materials, especially organics, transported on Titan's surface and in its atmosphere?—On Titan, as on Earth and Mars, multiple geologic processes act to transport materials. Dunes imply saltation of organic-rich sands (Lorenz et al. 2006b; Soderblom et al. 2007; Radebaugh et al. 2008; Janssen et al. 2009, 2016). Dendritic networks, rounded rocks, deltas, and alluvial fans indicate erosion of bedrock and redistribution of sediment by flowing liquids and mass wasting (Tomasko et al. 2005; Barnes et al. 2007b; Jaumann et al. 2008; Lorenz et al. 2008b; Le Gall et al. 2010; Burr et al. 2013; Birch et al. 2016; Cartwright & Burr 2017; Radebaugh et al. 2018). Evaporitic deposits suggest transport of organics in solution (Barnes et al. 2011; MacKenzie et al. 2014; MacKenzie & Barnes 2016).

Redistribution of material governs Titan's habitability by regulating the local availability of organic solids. Winds gather organic sand into vast dune fields (Lorenz et al. 2006b; Barnes et al. 2008; Radebaugh et al. 2008; Le Gall et al. 2011; Rodriguez et al. 2014), but the mechanisms that manufacture the organic sand particles are not understood (Barnes et al. 2015). In addition, wind models of net transport have not been directly verified (Tokano 2010; Radebaugh 2013; Malaska et al. 2016). Rounded cobbles suggest fluvial transport (Figure 1; Tomasko et al. 2005; Le Gall et al. 2010), but it is not known how far they were transported (Burr et al. 2006) or from what source material they might have eroded (Table 3). Understanding the provenance of surface clasts and transport rates as context for sampled materials will address these unknowns. Dragonfly will constrain the dominant transport processes, active transport rates, and sources of material in the equatorial region to understand how local availability of organic material controls Titan's habitability. *Science goal C*: determine the rates of processes modifying Titan's surface and rates of material transport.

3.2.1. Science Objective C1: Determine Conditions for Aeolian Transport

Dragonfly will study aeolian transport via passive and active experiments to quantify the importance of winds in mobilizing organic material on Titan's surface. Individual sand grains on Titan are expected to be 300–700 μm in diameter, and the estimated threshold wind speed for saltation is $\sim$1 m s^{-1} (Burr et al. 2006, 2015; Lorenz & Zimbelman 2014); however, both values are based on theoretical studies and laboratory analogs, not empirical Titan data.

Passive measurements—Measuring wind speed at the surface and correlating with images of surface changes (e.g., translation of ripples) will determine the conditions necessary for saltation, similar to experiments conducted by Curiosity on Mars (Bridges et al. 2017). Simultaneous measurement of wind speed and direction will determine the net sand flux vector; sand transport only occurs above the saltation threshold and scales as v^3, so the highest wind speeds are of greatest significance. (Imaging before and after landing can provide context regarding the disturbance of surface material by Dragonfly, expected to be minor, as shown in Lorenz et al. 2018b.)

Active measurements—Dragonfly will also conduct controlled saltation experiments while on the surface by monitoring the response of surface particles while spinning one or more rotors at different settings to generate known wind conditions to measure threshold wind speeds for saltation.

3.2.2. Science Objective C2: Determine the Transport Mode and History of Clastic Materials

Dragonfly will also investigate the role of other modes of material transport by constraining the local provenance of sampled materials. For example, interdune areas on Earth vary: many are covered in gravel derived from bedrock, but others consist of evaporite cement cobbles. Cassini evidence hints that Titan's interdunes also vary (Barnes et al. 2008; Radebaugh et al. 2008; Bonnefoy et al. 2016). In addition, at Selk Crater, rocks from deeper layers may be exposed by mass wasting of the crater walls, potentially affording a unique opportunity to dive into Titan's geologic past.

We will measure the size, frequency, and spatial distribution of cobbles (defined as >6.4 cm) and larger rocks from surface panoramas. High-resolution images will be used to characterize the size distribution (quantified by the Inclusive Graphic Standard Deviation metric; e.g., Blott & Pye 2001), shape, and roundedness of grains within individual clasts. Grain shape primarily relates to lithology, as well as physical erosion and weathering; rounding primarily indicates greater transport distance and/or duration. Clast size distributions are also an indicator of transport velocity and vigor, thereby constraining the depositional regime of the grains (i.e., fluvial, alluvial, aeolian, and mass wasting; e.g., Krumbein & Sloss 1951; Ibbeken 1983; Yingst et al. 2007, 2008). Thus, by combining these data with material transport rates on Titan, we can constrain the provenance of transported sediments (Collins 2005; Perron et al. 2006). This strategy is derived from those employed by in situ exploration on Mars. For example, textural analyses conducted for Martian soils with microscopic images from Spirit, Opportunity, and Curiosity (e.g., McGlynn et al. 2011; Cousin et al. 2017) have facilitated the identification of transport processes and postulation of formation models.

3.2.3. Science Objective C3: Determine the Geologic Context of Sampled Materials

Cassini and Huygens revealed a wide range of aeolian and fluvial processes at work on Titan's surface (Tomasko et al. 2005; Lorenz et al. 2006b, 2008b; Barnes et al. 2007b, 2008, 2015; Jaumann et al. 2008; Keller et al. 2008; Radebaugh et al. 2008, 2018; Le Gall et al. 2010; Burr et al. 2013; Radebaugh 2013; Lorenz 2014; Birch et al. 2016; Bonnefoy et al. 2016; Cartwright & Burr 2017). Dragonfly will place sampled material into compositional context with local geology by documenting the morphology, color and texture, and characteristics of geologic features and surface materials (Table 3), comparing clast color to that of observed landforms and surface materials to constrain the provenance of samples. Huygens' spectrometer indicated color variability of the surface at visible wavelengths (Karkoschka & Schröder 2016a), sufficient for visible color imaging to recognize commonalities between rocks, sediments, and outcrops. Imaging of fluorescence (Hodyss et al. 2004; Lorenz et al. 2017) under UV illumination will reveal certain organics. We can thereby extrapolate the compositions of sampled material to features around the rotorcraft lander.

3.2.4. Sampling Targets for Goal C

These objectives constrain the modes and rates of transport and thus accumulation of surface materials, thereby providing crucial context for all compositional measurements. Surface imaging by Dragonfly's cameras (DragonCam Lorenz et al. 2018b) will be acquired at each science sampling site. Dragonfly's mobility is key for this investigation, affording the opportunity to explore a variety of geologically diverse locations.

3.3. Goal D: Mixing Water and Organics

Science question: Where and how has liquid water been in contact with organic material?—An ice shell separates Titan's organic-rich surface from the liquid-water subsurface ocean (Iess et al. 2012), but the extent of that separation remains unknown. Cassini-Huygens' geophysical, gravitational, and electric-field data and models constrain the ice-shell thickness to 25–200 km (Tobie et al. 2006; Mitri & Showman 2008; Deschamps et al. 2010; Nimmo & Bills 2010; Béghin et al. 2012; Iess et al. 2012; Hemingway et al. 2013; Baland et al. 2014; Sohl et al. 2014; Durante et al. 2019). Mechanisms that allow mixing of organics and liquid water on Titan include melting of the water-ice crust during impact cratering (Artemieva & Lunine 2003, 2005; Zahnle et al. 2014) and transport of surface organics down to the subsurface ocean. Another possibility is eruption of subsurface water by cryovolcanic processes (Sotin et al. 2005; Barnes et al. 2006; Soderblom et al. 2009; Lopes et al. 2013; Nixon et al. 2018), but such features have proven challenging to identify definitively, and durations over which individual flows remain liquid could be quite short (Davies et al. 2010; Neish et al. 2018).

Impact craters provide known locations for mixing of organics and liquid water (Neish et al. 2018). Melt volume correlates with impact energy and thus crater size and morphology (Section 5; Pierazzo et al. 1997; Artemieva & Lunine 2003, 2005; Kraus et al. 2011; Elder et al. 2012). Cassini has identified several impact craters 75 to >300 km in diameter (Wood et al. 2010; Neish & Lorenz 2012; Hedgepeth et al. 2020). The melt in a 150 km diameter crater on Titan could remain liquid up to 10^4 yr (O'Brien et al. 2005; Davies et al. 2010).

Organic material could also be brought downward through the crust by burial and subsidence, seeding prebiotic chemistry in the water ocean, as well as possible perched liquid-water sills or magma chambers. Bulk downward transport of organics could also be driven by crustal tectonism, perhaps driven by convection in the lower crust. There is evidence for tectonics on Titan in the form of mountain ridge belts (Radebaugh et al. 2011; Cook-Hallett et al. 2015; Liu et al. 2016), but without adequate understanding of the thickness and nature of the lithosphere and the frequency of tectonic activity, the potential for organic exchange cannot be determined. To assess the habitability potential of liquid-water environments on Titan, Dragonfly will constrain which mechanisms operate to mix liquid water with organic compounds. *Science goal D*: constrain what physical processes mix surface organics with subsurface ocean and/or melted liquid-water reservoirs.

3.3.1. Science Objective D1: Measure Current Lithospheric Activity and Constrain Past Processes

Dragonfly will reveal the seismic activity of an ocean world by listening for quakes generated by the tidal deformation of Titan's ice crust (Mitri & Showman 2008). Cassini gravity measurements showed that Titan's crust deforms significantly over the course of its tidal cycle (Iess et al. 2012). Such deformation controls significant tectonic activity at Europa (Hoppa et al. 1999; Greenberg et al. 2003; Hand 2017; Vance et al. 2018) and Enceladus (Hurford et al. 2007), and Titan's unusually high eccentricity could allow tidal forces to drive tectonism despite Titan's longer orbital period than those other moons (Sagan & Dermott 1982; Sohl et al. 2014). Temporal clustering of seismic events with orbital phase would reveal the extent to which tidal forces control cracking and faulting across Titan.

Identifying spatial trends in activity through seismic monitoring along the traverse toward Selk Crater could reveal whether tidal forces activate regional faults. Different properties of the near-surface material could also be determined based on differences in transmission of seismic signals (Stähler et al. 2018, 2019; Lognonné et al. 2020).

Tectonic activity can also manifest as surface features like joints and faults. Imaging of the spacing and orientation of such features would provide inputs to models of local stress fields, rheological properties, and erosion rates to constrain crustal processes that can exchange material between the surface and subsurface (Litwin et al. 2012). Identification of faults expressed as surface lineations and/or scarps would be indicative of the regional stress state and help to constrain modes of stress generation and release, as has been done for other icy satellites (e.g., Patthoff et al. 2019). The power of combining imaging and seismic monitoring was recently demonstrated by InSight, which confirmed the Cerberus Fossae system, inferred as extensional systems from orbital images, as a source of normal faulting-style marsquakes (Banerdt et al. 2020; Giardini et al. 2020; Brinkman et al. 2021).

3.3.2. Science Objective D2: Constrain the Depth to Titan's Liquid-water Ocean

Numerical models demonstrate how crustal thickness affects convective and conductive layering within the ice shell and on the interior structure (Mitri & Showman 2008). The current range of possible thicknesses derived from Cassini data, however, cannot uniquely determine the bulk physical properties of or structure within Titan's lithosphere.

Seismic activity—Modeling of seismic waveforms will allow us to infer the thickness of the ice shell based on reflection and transmission of the seismic source signal. If Dragonfly detects tectonic cracking events, then we can determine the ice-shell thickness from the timing of reflected P-wave phases, similar to the technique proposed for Europa lander missions (e.g., Lee et al. 2003; Panning et al. 2006; Vance et al. 2018). Even in the absence of tectonic events large enough to rise above ambient noise, the ambient noise itself can be used to extract a P-wave reflectivity response via autocorrelation of the noise, which can constrain shell thickness and properties, as demonstrated in terrestrial studies on the Antarctic Amery Ice Shelf (Zhan et al. 2013).

A significant new body of work on ocean world seismology has been motivated by the prospects of seismic measurements on a Europa lander (e.g., Panning et al. 2018; Hurford et al. 2020). Recent simulations of seismic propagation in Titan interior models (Stähler et al. 2018, 2019; Figure 3) show that the ice layer structure retains more seismic energy near the surface than is typical for terrestrial planets. Indeed, the rich array of waves in icy moons demands a new taxonomy to identify the various modes, e.g., Scholte waves at the ocean/mantle interface. Large events can even provide information about deeper structure, for example, signatures diagnostic of an Ice-VI layer at the base of the ocean (Stähler et al. 2018), as well as the crustal thickness. Quantitative analysis (Panning et al. 2018) suggests an expected generation rate of Titanquakes by scaling lunar seismicity by Titan's tidal dissipation (e.g., a 3.8 mag event expected to produce signals comparable to those shown in Figure 4 should occur 0.02–10 times per Titan day (Tsol); see also Hurford et al. 2020). Analyses of wind and pressure noise for Mars (Murdoch et al. 2017a, 2017b) can be scaled to Titan to show that these should not be limiting factors for a ground-deployed instrument.

Single-station techniques have matured in recent years, partly in connection with the InSight mission. While longer-period surface wave techniques for single stations were expected to be a powerful tool for Mars structure based on pre-mission expectations (Panning et al. 2015, 2017), results have instead come from observations of body waves. These have been used for detection and distance estimation for hundreds of events (Clinton et al. 2020), including precise locations and source mechanism estimates for the clearest events (Giardini et al. 2020; Brinkman et al. 2021) and determination of subsurface structure (Lognonné et al. 2020). While long-period surface wave energy appears promising for ocean world structure determination due to energy trapped within the ice shell (e.g., Panning et al. 2006; Stähler et al. 2018), multiple single-station techniques are available using body waves as well (Stähler et al. 2018). The ability of DraGMet to perform low-power continuous monitoring with event detection means it is realistic to anticipate detection of events with recurrence intervals of <0.1 per Tsol, such that even nondetections become scientifically significant.

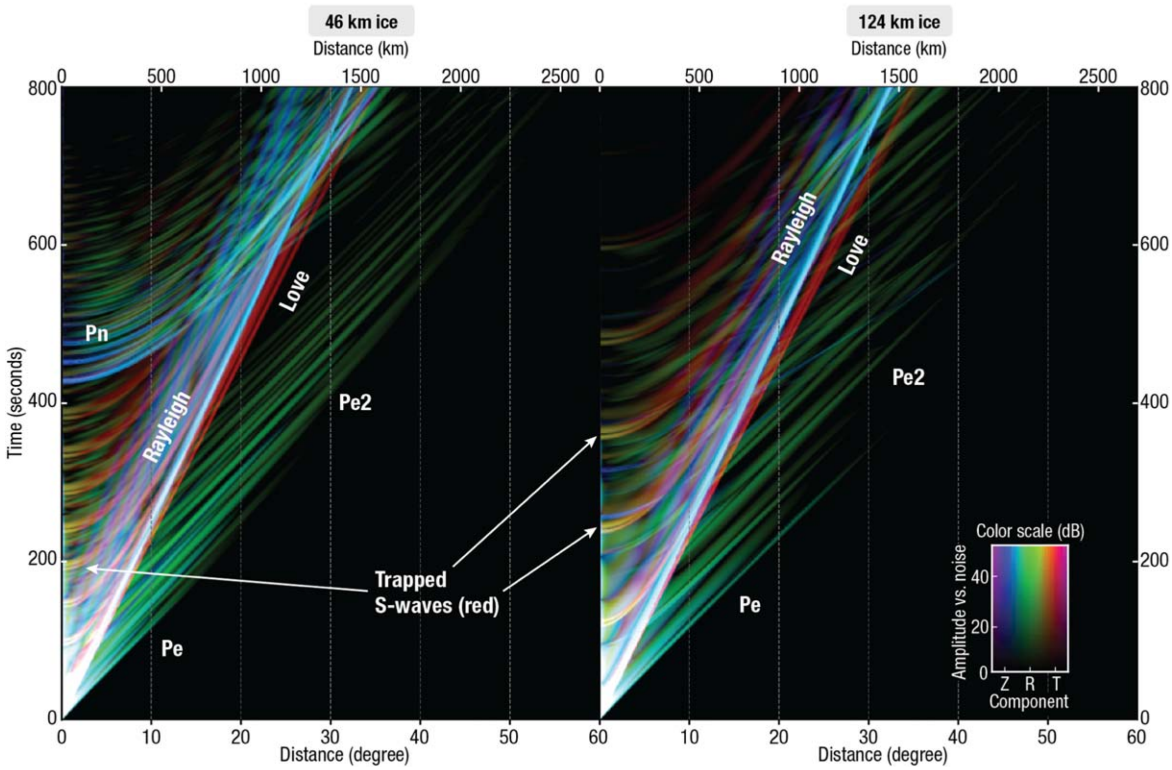

Figure 3. Simulated stacked seismograms for two Titan interior models: 46 km thick ice crust (left) and 124 km thick ice crust (right) over 410 km thick water ocean with 3.3% NH_3 (Panning et al. 2018; Stähler et al. 2018). Colors show the vertical (Z) and horizontal (radial and tangential) components of ground motion. The arrival times of Rayleigh and Love waves are a measure of source distance, while trapped S-waves indicate crustal thickness. The vertical gray lines at $\sim$20° indicate the approximate distance corresponding to the records shown in Figure 4.

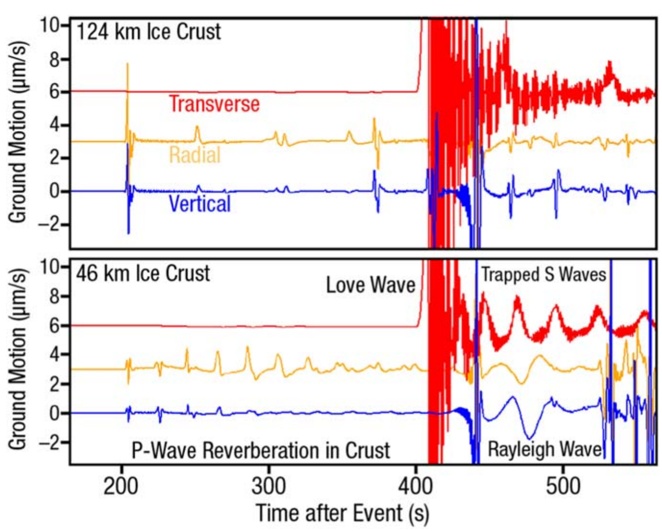

Figure 4. Measured waveforms from Figure 3 at a distance of 18° ($\sim$800 km). The train of P-wave arrivals (200–350 s) is another straightforward diagnostic of ice crust thickness. Rayleigh and Love wave amplitudes, $\sim$20 and $>$100 μm s^{-1}, respectively, may be detectable even with Dragonfly's skid-mounted geophones (Lorenz et al. 2018b).

Schumann resonance—On Earth, the conductive ionosphere and ocean surface act as waveguides, forming a resonant cavity for electromagnetic waves. During its descent, Huygens observed electric-field signals with a frequency near $\sim$36 Hz (Béghin et al. 2007) that were interpreted as the signature of such a Schumann resonance cavity. However, it has also been suggested that the signals were artifacts (Lorenz & Le Gall 2020) of mechanical vibrations during Huygens' parachute descent.

The Schumann interpretation differs from the classic terrestrial paradigm, where lightning discharges excite the signals, which manifest predominantly in vertically polarized electrical waves. Instead (since lightning has not been observed on Titan), interaction with Saturn's magnetosphere could stimulate the resonance, seen by Huygens as horizontally polarized electric fields. As on Earth, the lower boundary of Titan's ionosphere serves as the top of the resonant cavity, but whereas the lower boundary on Earth is the (conductive) land and sea, on Titan, it is the internal salty or ammoniacal water ocean. One interpretation of the Huygens measurement is that the lower boundary lies 55–80 km beneath Titan's surface (Béghin et al. 2012). However, this estimate does not include uncertainties associated with the Schumann resonance model (e.g., ionospheric structure; Lorenz & Le Gall 2020), and the very limited spectral resolution of the Huygens measurements limits the measurements' ability to constrain the model.

Despite the challenges of this arena, Dragonfly aims to detect natural time-varying electric fields, if they exist. By making measurements for extended periods on the surface (without the confounding noise of Huygens' descent), more sensitive spectral analysis can be applied; if multiple Schumann frequencies are detected (often five or more peaks are seen at Earth), then their relative amplitudes may constrain their generation mechanism. Variation in their character with ionospheric conditions (e.g., local solar time) may help reduce systematic uncertainties in model interpretation as crustal thickness.

3.3.3. *Science Objective D3: Determine Availability of Water Ice*

Dragonfly will seek to detect water ice on and near Titan's surface in different geologic settings to determine the potential for mixing with organics. Cassini has documented localized areas of water-ice enhancement on Titan (Griffith et al. 2019), and Dragonfly will target such areas, including interdune areas (Barnes et al. 2008), ejecta deposits south of Selk Crater, the interior margins of the crater floor (Solomonidou et al. 2020), and potential melt flow features east of the crater (Soderblom et al. 2010a; Neish et al. 2015; Janssen et al. 2016; Werynski et al. 2019; Lorenz et al. 2021). DraGNS will measure the bulk elemental content of each science landing site to constrain the water content. Ice provenance (e.g., crustal ice, former impact melt, or ejecta) will be interpreted from landscape morphology and abundances of certain organic and inorganic compounds, making it possible to test ice-origin hypotheses (Table 3) and constrain exchange mechanisms with the subsurface ocean.

3.3.4. Goal D Sampling Targets

Compositional investigations (science objective D3; Table 3) require measurements of (α) predominately organic sediments and (β, γ, or δ) material with a water-ice component (Table 3). Composition at depth can differ from surface material (Janssen et al. 2016), so to be able to detect the presence of near-surface water ice beneath an organic veneer, DraGNS will be sensitive to bulk composition deeper than ∼10 cm below the surface. Measurements will be informed by DragonCam imaging of geologic structures and relationships.

4. Search for Biosignatures

4.1. Goal E: Chemical Biosignatures

Our understanding of biology remains based on a single sample set: life on Earth. Therefore, a main goal of solar system exploration is to ascertain whether life has originated separately from that on Earth: a “second genesis.” Detection of extraterrestrial life in our solar system would be a revolutionary discovery, further suggesting that life may arise readily in diverse planetary environments throughout the universe. As is the case for all potentially habitable bodies, whether Titan has supported the development of biological systems is currently unknown, but the possibility of past, or even extant, life cannot be ruled out. With the known necessary ingredients present on its surface—energy, solvents, and essential elements such as carbon, hydrogen, nitrogen, oxygen, and possibly phosphorus and sulfur (CHNOPS)—Titan is one of the best places in the solar system to search for such life (Simakov 2000, 2004, 2012; Sarker et al. 2003; McKay 2004, 2016; Schulze-Makuch & Grinspoon 2005; Shapiro & Schulze-Makuch 2009; Raulin et al. 2010; Neish et al. 2018).

Were life to have existed in a transient Titan melt pool, it would have left compositional biosignatures in the now-solidified ice. Such biosignatures would be protected from degradation by galactic cosmic rays due to Titan’s thick atmosphere and from chemical weathering due to the insolubility of water ice in liquid hydrocarbons (Lorenz & Lunine 1996). Biological processes produce compounds with distinct abundance patterns compared to abiotic processes (McKay 2004; Figure 5). Biology also prefers molecules of a single handedness, or chirality (Halpern 1969; Bada & McDonald 1996; Bada 1997; Aubrey 2008). These and other measurable chemical clues could represent signs of past or extant life (Figure 6).

Titan also offers the opportunity to more broadly examine assumptions about habitability by exploring whether life can form or exist in a solvent other than water. Life, but not as we

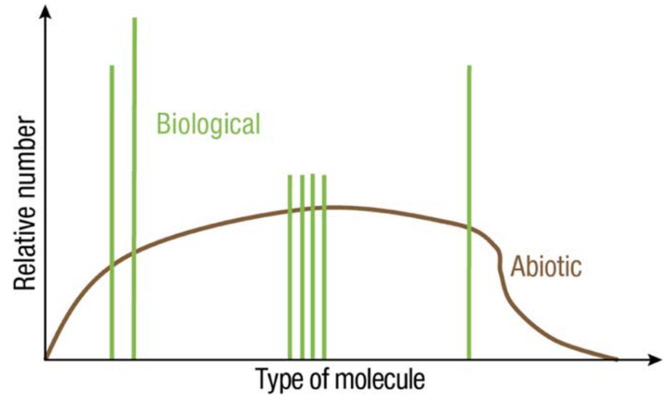

Figure 5. Comparison of biogenic with nonbiogenic distributions of organic material. Abiotic processes typically produce smooth distributions of organic material (brown). Biology, in contrast, selects and uses a highly specific set of molecules (green), e.g., chiral amino acids on Earth. After Figure 1 in McKay (2004).

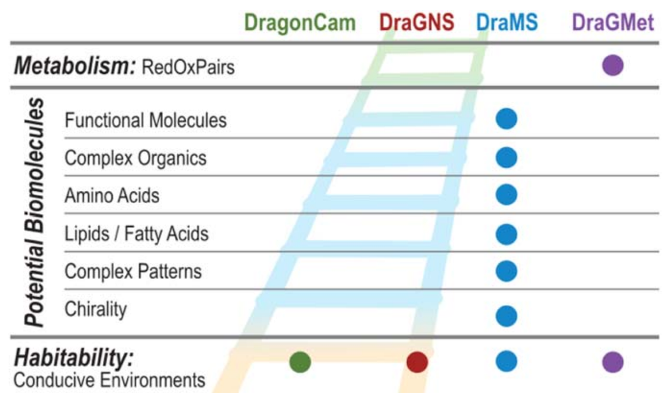

Figure 6. Dragonfly’s payload is designed to identify chemical features associated with rungs on the NASA Astrobiology Life Detection Ladder (Neveu et al. 2018).[26]

know it, might have existed or exist today within Titan’s liquid hydrocarbons (McKay 2004, 2016; Stevenson et al. 2015). Low solubility and slow reaction rates challenge terrestrial expectations for biochemical mechanisms of hydrocarbon-based life, but under Titanian conditions, alternate pathways could permit parallel processes in liquid hydrocarbon media (Stevenson et al. 2015; Rahm et al. 2016; Lv et al. 2017). Signatures of such life, were it to exist, could consist of abundance patterns of useful compounds or of spatial gradients in the abundance of H_2, which could serve as a metabolic input (McKay & Smith 2005).

Science question: Are there chemical signatures of water- or hydrocarbon-based life on Titan?—Although life as a concept continues to elude definition (Cleland & Chyba 2002), life on Earth exhibits common chemical characteristics (McKay 2004). Terrestrial biology, or life as we know it (LAWKI), relies on specific molecules like amino acids, lipids, and nucleic acids. Other biochemistries might use different functional molecules. Therefore, patterns of molecular abundances in comparison to abiotic abundances, distributions, and complex pathway assessments can be a powerful class of biomarkers (Benner & Hutter 2002; McKay 2016; Marshall et al. 2017). Evaluating the relative abundance and distribution of organic compounds (Figure 5) is diagnostic for biology that uses liquid water as a solvent (water-based life), as well as biology that might use liquid hydrocarbons (hydrocarbon-based life; Lovelock 1965; McKay 2004). A broad-based search for multiple chemical biosignatures (Figure 6) minimizes assumptions about the nature of potential life, a valuable lesson from Viking life-detection experiments (Klein et al. 1976; Ballou & Wood 1978; Klein 1979) and the same strategy proposed for a Europa lander (Hand 2017). Dragonfly will perform a broad, multi-faceted search for chemical signatures that would be indicative of past or extant biological processes on Titan, not only climbing the Ladder of Life Detection[26] (Figure 6; Neveu et al. 2018) but also building wide rungs on which future ocean world missions can stand. Crucially, this strategy can identify several different potential biosignatures, as no single observation in isolation can be considered definitive evidence. *Science goal E*: perform a broad-based search for signatures indicative of past or extant biological processes.

4.1.1. Science Objective E1: Determine Enantiomeric Abundance of Chiral Molecules

Dragonfly will identify whether biologically useful molecules demonstrate a distinct handedness consistent with biofunctionality. The premier example of biochemical selectivity is homochirality: life on Earth uses only left-handed (L) versions of amino acids in proteins and only right-handed (D) versions of sugars, but not their mirror images (Aubrey 2008). For molecules that do not exhibit such preferences in abiotic systems, detection of homochirality would be a powerful indication of biological activity, regardless of whether the solvent is water or hydrocarbon (Creamer et al. 2016). We will assess chirality via chromatographic methods (Goesmann et al. 2017).

4.1.2. Science Objective E2: Determine if Patterns Exist in Molecular Masses and Distribution

Dragonfly will identify the molecular motifs of functional molecules, if present, by determining the composition of organic and water-ice materials on the surface of Titan. Compositional assays of both organic and water-ice materials will allow us to look for patterns in abundance and/or structure.

Abundance patterns—A key feature of life on Earth is that it is selective in the basic molecules it uses, e.g., the "Lego Effect" (Lovelock 1965; McKay 2004; Marshall et al. 2017). The blocks used can be formed abiotically, but selective use in and production by biological processes creates a distribution distinct from abiotic processes (Figure 5). For example, of $\sim$500 known amino acids, just 22 are coded for by eukaryotic DNA (Gutiérrez-Preciado et al. 2010). Similarly, abiotic synthesis creates carbon chains of random length, while eukaryotic carboxylic acid chain lengths occur with a strong even-over-odd preference and a restricted range (Balkwill et al. 1988; McCollom 1999; Costello et al. 2002; Lester et al. 2007; Steger et al. 2011). Furthermore, while geochemical methane sources also produce nonmethane hydrocarbons in amounts that decrease smoothly with increasing mass, methanogens produce methane but very few nonmethane hydrocarbons (McKay 2008).

Structural patterns—The utility of a molecule's structure drives the biological synthesis of certain structural isomers over others. For example, terrestrial metabolism primarily uses glucose; although galactose has the same molecular composition, a structural difference (relative positions of hydroxyl groups) makes glucose preferable. Dragonfly will identify potentially isomeric molecules and conduct analyses to isolate any structural patterns.

4.1.3. Science Objective E3: Determine if Metabolic Processes Are Active on the Surface

Dragonfly can identify gradients in the relative abundances of potential consumables in Titan's lower atmosphere that could signify active metabolic processes. Life that is widespread affects its environment: the majority of O_2, CO_2, and CH_4 in Earth's atmosphere are biological products. On Titan, because of its availability and potential as a reactive fuel source, H_2 is the most promising atmospheric constituent for showing a biological effect. Intriguing and controversial models based on low-precision Huygens data suggest a flux of hydrogen into Titan's surface (Strobel 2010). If life were consuming atmospheric hydrogen, it would have a measurable effect on the hydrogen mixing ratio in the troposphere (McKay & Smith 2005), depending on the consumption rate. Dragonfly will construct a vertical profile of H_2 abundance to determine if there is, indeed, a net flux into the surface (Lorenz et al. 2019).

4.1.4. Science Goal E Sampling Targets

The expectation is that biologically relevant monomers are more likely to be present in samples from water-ice material. However, establishing whether a pattern is consistent with biological control necessarily requires a broad contextual baseline (Hand 2017). Dragonfly is therefore required to evaluate the abundance and distribution of compounds in organic sediments, as well as in material with a water-ice component.

4.1.5. Biosignature Search Discussion

Titan's high potential for prebiotic chemistry and astrobiologically interesting materials includes the following factors:

1. opportunities for mixing of organic material with liquid water at Titan's surface in the past (Lorenz et al. 2021),
2. the possibility of material transfer from the surface to the liquid-water ocean (and possibly vice versa), and
3. the potential for liquid methane to function as a solvent in the development of a hydrocarbon-based biological system.

Here we elaborate on possible scenarios for the development of biological systems on Titan and accessibility to Dragonfly. These include

1. extinct water-based life (LAWKI) in a previously warm liquid-water surface reservoir(s), now frozen (Neish et al. 2018);
2. extinct or extant water-based life in Titan's subsurface ocean (Fortes 2000); and
3. extinct or extant hydrocarbon-based life in Titan's lakes, seas, and/or subsurface liquid hydrocarbon reservoirs (McKay & Smith 2005; McKay 2016).

Similar to other targets in the outer solar system, LAWKI is not expected to be extant in surface deposits, but chemical

[26] https://astrobiology.nasa.gov/research/life-detection/ladder/

Table 4
Dragonfly's Broad-based Approach to Our Search for Potential Signatures of Past or Extant Biological Systems

Measurement Strategy	Signature(s) of			Key References
	Water-based Life	Hydrocarbon-based Life	Abiotic Processes	
Determine enantiomeric abundance of chiral molecules (science objective E1)	• Enantiomeric excess of sugars or amino acids	• Enantiomeric excess of molecules or compounds unusual for terrestrial biochemistry that could serve as analogs of sugars or amino acids	• Low enantiomeric excess in observed sugars and amino acids (similar to those seen in meteorites)	Meierhenrich (2008); Creamer et al. (2016)
Determine if patterns exist in molecular masses and distribution (science objective E2)	• Peaked abundance of certain molecules versus carbon number	• Peaked abundance of certain molecules with carbon number different from expected for water-based life (i.e., water-insoluble or easily hydrolyzable molecules)	• Smooth abundance distribution of carbon species• Comparison to complex pathway assessments of known abiological equivalents	Hartgers et al. (2000); Marshall et al. (2017)
	• Higher abundance of high molecular weight amino acids	• High abundance of high molecular weight amino acid analogs	• Low molecular weight amino acid prevalence	Higgs & Pudritz (2009)
	• Lack of "meteoritic amino acids" and presence of terrestrial proteinogenic amino acids		• Presence of "meteoritic amino acids" and lack of terrestrial proteinogenic amino acids	Higgs & Pudritz (2009)
	• Even-numbered chain lengths of carboxylic acids	• Preference for chain lengths of potentially biosynthetic pathways	• Smooth distribution of even- and odd-numbered chain lengths of carboxylic acids	Balkwill et al. (1988); McCollom (1999); Costello et al. (2002); Lester et al. (2007); Steger et al. (2011)
Determine whether metabolic processes are active on the surface (science objective E3)		• H_2 flux into the surface	• H_2 flux into the surface	McKay & Smith (2005); Lorenz et al. (2019)

Note. Different possible scenarios and the implications of detections or measurements of various molecules, if present, are presented in light of water-based life, hydrocarbon-based life, and abiotic processes.

biosignatures could be preserved (scenario 1) or admit the possibility of past or extant life in the subsurface ocean (scenario 2) if material is brought to the surface (e.g., via cryovolcanism). As a surface-sampling mission, Dragonfly will be able to assess prebiotic chemistry and search for evidence of water-based biosignatures formed at the surface (scenario 1) or deposited on the surface (scenario 2). Cryovolcanic features have proven challenging to identify definitively on Titan, however, and the degree of connectivity to the subsurface ocean (scenario 2) is unknown. Selk Crater (Soderblom et al. 2010a) is targeted by Dragonfly as a site where liquid water is known to have been present on the surface for an extended period of time in the past, an environment conducive to the formation of molecules of biological interest (Neish et al. 2008, 2009, 2010, 2018; Poch et al. 2012; and potentially scenario 1).

In addition to sampling materials with a water-ice component, Dragonfly will measure the equatorial sands where geological processes have transported and collected organic products (Lorenz et al. 2006b; Rodriguez et al. 2014; Malaska et al. 2016), making the dunes a good location to potentially constrain the possibilities for hydrocarbon-based biosignatures (scenario 3).

Dragonfly science measurements are generally agnostic to water- or hydrocarbon-based biologies (as recommended by the Europa Lander science definition team; Hand 2017), relying on the results from the compositional survey of goal A and subsequent modeling efforts to put potential biosignatures into the proper context. This approach is summarized in Table 4.

5. Landing Site and Traverse

5.1. Landing Site 1 in Shangri-La Provides Access to Organic Sediments in Water Ice

Geological processes concentrate the products of Titan's atmospheric chemistry into organic sediments that are transported by aeolian and fluvial activity. Sand particles collect in the extensive equatorial dune fields (Lorenz et al. 2006b; Rodriguez et al. 2014; Malaska et al. 2016). These vast carbon sinks are thus an ideal location to assess prebiotic chemistry and search for potential signatures of past biological activity.

Landing site 1 (LS1) is targeted within a portion of the Shangri-La sand sea, part of Titan's best-characterized geomorphologic unit (Figures 7 and 8). Titan's organic sand seas comprise longitudinal dunes hundreds of kilometers long spaced 2.0–3.5 km apart (Savage et al. 2014) and resemble terrestrial silicate longitudinal dunes in morphology and extent (Lorenz et al. 2008c; Radebaugh et al. 2008). In addition to being an ideal location to achieve high-priority science, Titan's dunes have been well characterized by Cassini and provide safe conditions for first landing (Lorenz et al. 2018b).

Despite the name, sand seas are typically not completely covered by sand; instead, dunes can be separated by flat, sand-free interdunes 1.0–2.5 km wide (Barnes et al. 2008; Savage et al. 2014). Sand covers only 40% of the Namib sand sea in SW Africa, with sand-free, gravel interdunes comprising the remaining 60% (Lancaster 1989). Titan's interdunes have been resolved spatially (Barnes et al. 2008; Le Gall et al. 2011) and spectrally (Bonnefoy et al. 2016), revealing predominately icy interdunes that match the spectral properties of the Huygens landing site (HLS). This correlation suggests that the Shangri-La interdunes are likely to include water-ice gravels, potentially a fine-grained layer damp with condensed methane (Figure 1; Niemann et al. 2005; Tomasko et al. 2005; Zarnecki et al. 2005; Lorenz et al. 2006b; Keller et al. 2008; Williams et al. 2012; Lorenz 2014; Karkoschka & Schröder 2016b). Targeting LS1 in an interdune area provides proximity to both organic sands and material with a likely water-ice component.

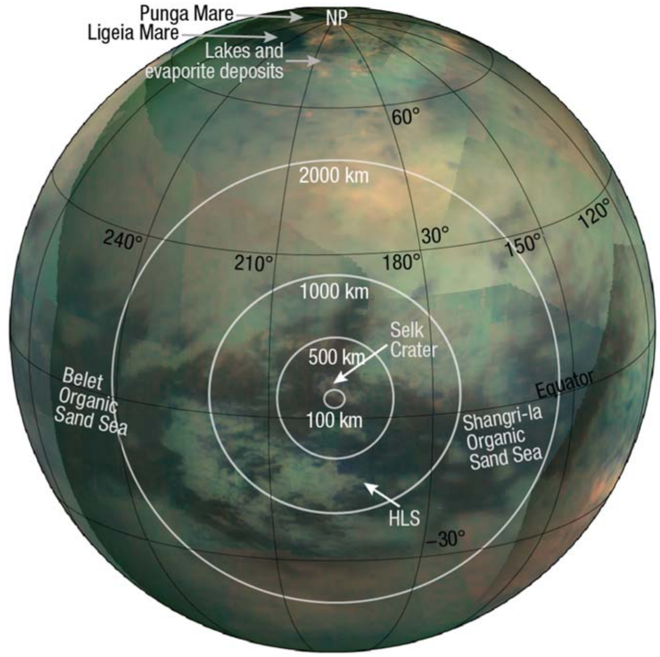

Figure 7. Global landing site context. Dragonfly is targeted (Landing Site 1 (LS1) at center) to land at ∼ 3°.7N, ∼ 198°.2W in the Shangri-La organic sand sea, centered ∼134 km south of Selk Crater. This site lies ∼750 km north-northwest of the Huygens Landing Site (HLS).

5.2. Traverse to Selk Impact Crater to Access Previously Melted Water Ice

To be sure of sampling previously melted water ice, Dragonfly will traverse to Selk Crater (Figure 8; Lorenz et al. 2021), documenting terrain and compositional variations along the way. This traverse will cross several distinct surface units identified in Cassini data, including the edge of Selk's proximal ejecta deposits. This material is similar in average composition to the HLS (Soderblom et al. 2010b) and therefore represents another prime target for sampling material with a water-ice component.

Selk itself is a relatively young, 80 km diameter impact crater, the interior of which shows the spectral signature of organic sand, with water-ice material near the edges of the crater floor (Lorenz et al. 2021). Hydrocode simulations of the formation of an ∼80 km diameter crater on Titan generate ∼100 km^3 of melt, 70%–90% of which (depending on impact angle) is deposited within the crater; the rest is entrained in ejecta (Artemieva & Lunine 2003). Models, spectral data, and Titan's active fluvial erosion suggest exposures of water ice amid partial organic sediment cover, making Selk one of the best locations to find previously melted water ice to sample.

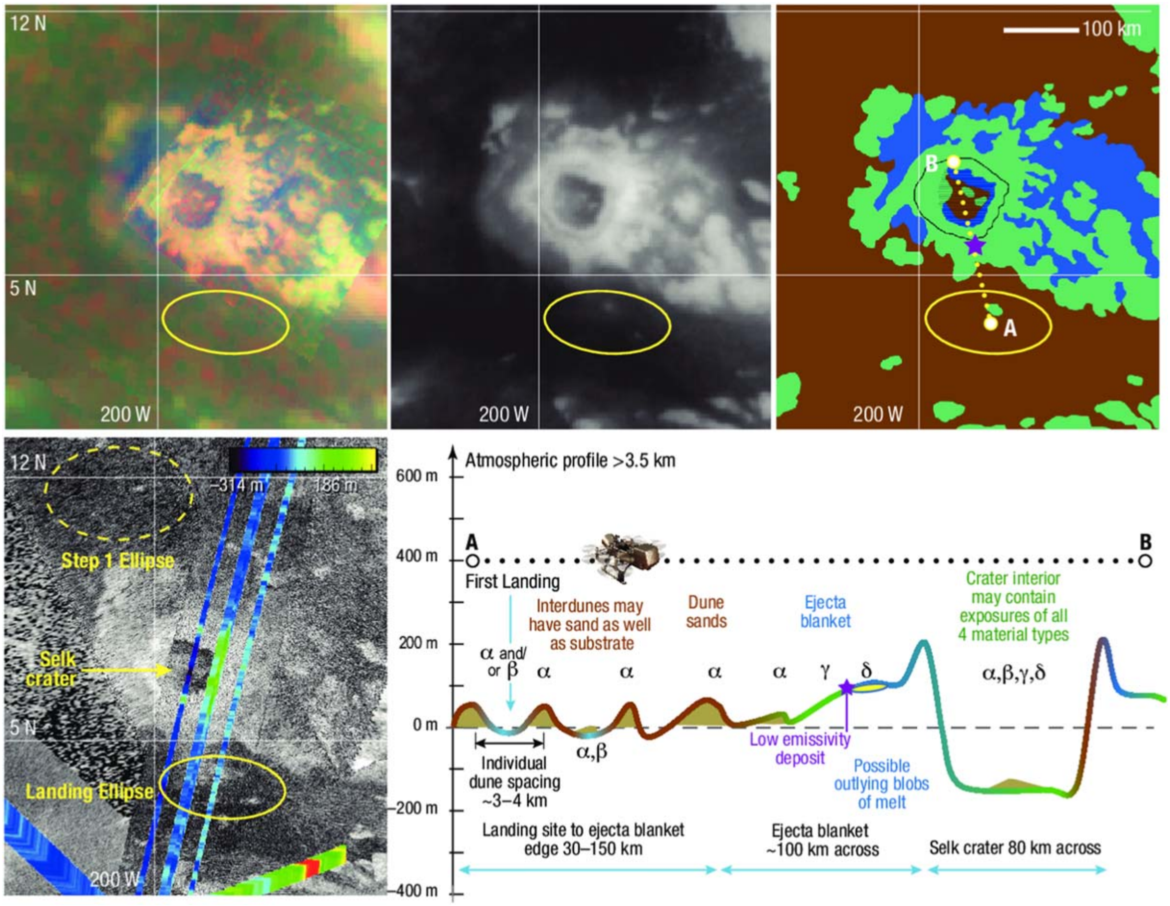

Figure 8. Views of the Dragonfly exploration region: top left, Cassini Visual and Infrared Mapping Spectrometer (VIMS); top middle, Imaging Science Subsystem at 938 nm; and bottom left, synthetic aperture radar (SAR), 2.2 cm, with color-coded topography (Stiles et al. 2009). The initial landing ellipse is indicated by the solid yellow oval on each map, and the dotted yellow line indicates a linear traverse for which geologic units (map at top right) and representative topography with $>200\times$ vertical exaggeration are shown (bottom right). VIMS illustrates the spectral diversity of Titan's surface: red, green, and blue channels are assigned to 5, 2, and 1.3 μm atmospheric windows, respectively. The spectral unit mapped in blue at top right has an enhanced water-ice spectral component and corresponds to materials labeled β and δ (bottom right; Table 3; additional blue areas may exist but are not resolved by VIMS). Cassini radiometry data indicate a low-emissivity deposit (purple star along traverse), which is also suggestive of water ice. The unit mapped in brown at top right correlates uniquely with organic sand dunes, material labeled α (bottom right; Table 3). And the unit mapped in green (bottom right; material labeled γ) corresponds to highlands terrain, like the channeled terrain near the HLS (Rodriguez et al. 2006; Barnes et al. 2007a; Soderblom et al. 2007). Areas of brighter radar return (bottom left) have higher roughness at the 2.2 cm scale, greater volume scattering, or greater reflectivity. The landing ellipse is dark in SAR because the area is both smooth and radar-absorptive. Astrodynamic and other factors that influenced the selection of the landing site and a review of available data sets on Selk are given in Lorenz et al. (2021).

6. Conclusion

Dragonfly was officially selected for flight by NASA as the fourth New Frontiers mission on 2019 June 27. Launch is planned for 2027, with Titan arrival in the mid-2030s, during the local northern hemisphere winter.

We designed the science of Dragonfly around the themes of prebiotic chemistry, habitability, and the search for biosignatures, with an explicit consideration of both water and hydrocarbon solvents. To address prebiotic chemistry, we will determine the inventory of prebiotically relevant organic and inorganic molecules and reactions on Titan. In the realm of habitability, we will determine the role of Titan's tropical atmosphere and shallow subsurface reservoirs in the global methane cycle, determine the rates of processes modifying Titan's surface and rates of material transport, and constrain what physical processes mix surface organics with subsurface ocean and/or melted liquid-water reservoirs. Our search for biosignatures will entail a broad-based search for signatures indicative of past or extant biological processes.

Our science goals led us to landing within the Shangri-La sand sea, where both organic sediments from the sand dunes and water ice of the interdunes would be available within a few kilometers of one another. To achieve the surface mobility necessary to traverse between the dunes and interdunes, we developed a system whereby the entire lander uses rotors to fly with vertical lift (Lorenz et al. 2018b). Calculation of the energetics of such a system led us to realize that large-distance traverses would be possible (Langelaan et al. 2017), greatly in excess of any previously achieved by planetary spacecraft. That additional range allowed us to target an impact crater, Selk, where previously liquid impact melt could be sampled.

The Dragonfly mission capabilities achieve many of the objectives previously derived for both surface landers and aerial vehicles (Lorenz 2008, 2009; Coustenis et al. 2011; Hall et al. 2011; Barnes et al. 2012) in flagship mission studies (Levine et al. 2005; Lunine et al. 2005; Lorenz et al. 2008a; Coustenis et al. 2009; Reh et al. 2009). The major outstanding unaddressed questions after Dragonfly's selection also require the global scope that can best be achieved with an orbiter mission. Ultimately, complementing Dragonfly with a small- or medium-class orbiter might achieve science at a scope comparable to that of three-element flagships (like those studied for the 2013–2023 Decadal Survey; Squyres & Soderblom 2011) without requiring the complexity or cost of a flagship mission.

Since selection, we have worked with NASA headquarters to establish a finalized list of level 1 science requirements for the Dragonfly project. The level 1 requirements serve to guide both mission development and operation but also to verify mission success after its execution. We include our list of level 1 requirements below both to further understanding of Dragonfly and its mission and to serve as a reference for future missions and proposers. We hasten to add that there are various ways to successfully write level 1 requirements, and that the approach that we use may or may not be applicable to or optimal for other mission concepts.

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Appendix
Dragonfly Level 1 Science Requirements

The Dragonfly primary science requirements map directly to the major science objectives targeted to realize the science goals of the Dragonfly mission, as discussed in the main text.

Dragonfly's Baseline Mission is designed with a specific focus on Titan's prebiotic chemistry and habitability, including assessing the potential for past and ongoing processes that may have brought organic material into contact with liquid water and investigating sites where such interactions may have taken place at the Selk impact structure.

The level 1 science requirements (SR-1–SR-5) flow from the five science goals (A–E in Sections 2, 3, and 4), with specific related aspects broken out as part of each requirement (e.g., SR-1a–SR-1d).

SR-1. Dragonfly shall determine the inventory of prebiotically relevant organic and inorganic molecules on Titan's surface in at least three geologic settings: dunes, interdunes, and impact crater deposits.

1. SR-1a. Measure the compositions of Titan's surface organic molecules containing as many as 40 carbon atoms (or up to 550 Da) at concentrations as low as 500 ppbw.
2. SR-1b. Measure or establish upper limits on abundances of elemental C, N, O, H, Na, Mg, P, S, Cl, and K, if present at $\geqslant 1$ weight percent, to $\leqslant 10\%$ relative precision.
3. SR-1c. Determine whether key molecules such as amino acids, nucleobases, lipids, and sugars containing as many as 16 carbon atoms (or up to 260 Da) are present at concentrations as low as 500 ppbw.

SR-2. Dragonfly shall identify sources and sinks of methane, determine their roles in Titan's methane cycle, and constrain the abundance of liquid methane in the near subsurface.

1. SR-2a. Measure atmospheric conditions at least 12 times per Tsol over a total of four different Tsols divided among at least two landing sites and including measurements of temperature, pressure, methane humidity, wind speed, and direction.
2. SR-2b. Measure or establish upper limits on the abundance of noble gases Ne and Ar (20–40 Da), if present at $\geqslant 10$ ppbv, to constrain Titan's atmospheric history.

SR-3. Dragonfly shall determine modes of material transport, surface modification processes, and sample provenance by observing sedimentary materials at landing sites.

1. SR-3a. Document sizes and colors of individual grains to spatial resolution $\leqslant 120\,\mu$m at sampling sites to put sampled materials in the context of materials observed in the terrain surrounding the lander.
2. SR-3b. Document geologic features and colors of materials at spatial resolution $\leqslant 1$ m in the terrain near the lander to a range of at least 50 m, covering $\geqslant 50°$ of azimuth at landing sites where sampling is performed.

SR-4. Dragonfly shall constrain the physical processes that mix organic material with liquid-water reservoirs or the subsurface ocean.

1. SR-4a. Determine whether Titan is seismically active by monitoring ground motion over at least 3 Tsols (diurnal/tidal cycles) with a sensitivity of $10\,\mu\mathrm{m\,s^{-1}}$.
2. SR-4b. Document geologic features at spatial resolution $\leqslant 1$ m in the terrain near the lander to a range of at least 50 m covering $\geqslant 50°$ of azimuth, including stereo coverage over $\geqslant 30°$ of azimuth.
3. SR-4c. Measure or establish upper limits on abundances of elemental O and H, if present at $\geqslant 1$ weight percent, to $\leqslant 10\%$ relative precision to constrain the presence of water ice at landing sites where sampling is performed.

SR-5. Dragonfly shall search for potential chemical signatures of water- or hydrocarbon-based biological processes.

1. SR-5a. Identify key molecular structures, including chirality, for molecules containing as many as 16 carbon atoms (or up to 260 Da) at concentrations as low as 500 ppbw.
2. SR-5b. Measure mass and abundance distributions of organic molecules containing as many as 40 carbon atoms (or up to 550 Da) at concentrations as low as 500 ppbw.
3. SR-5c. Measure atmospheric H2 abundance between 0.05% and 0.5%.

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