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Titan: Earth-like on the Outside, Ocean World on the Inside

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Abstract

Thanks to the Cassini–Huygens mission, Titan, the pale orange dot of Pioneer and Voyager encounters, has been revealed to be a dynamic, hydrologically shaped, organic-rich ocean world offering unparalleled opportunities to explore prebiotic chemistry. And while Cassini–Huygens revolutionized our understanding of each of the three “layers” of Titan—the atmosphere, the surface, and the interior—we are only beginning to hypothesize how these realms interact. In this paper, we summarize the current state of Titan knowledge and discuss how future exploration of Titan would address some of the next decade’s most compelling planetary science questions. We also demonstrate why exploring Titan, both with and beyond the Dragonfly New Frontiers mission, is a necessary and complementary component of an Ocean Worlds Program that seeks to understand whether habitable environments exist elsewhere in our solar system.

Unified Astronomy Thesaurus concepts: Titan (2186); Planetary science (1255); Natural satellite surfaces (2208); Planetary atmospheres (1244); Planetary climates (2184)

1. Introduction

At the turn of the millennium, advancements in ground-based and space-based telescopes enabled the first glimpses of Titan’s surface (e.g., Smith et al. 1996; Meier et al. 2000; Coustenis et al. 2001, 2003; Griffith et al. 2003). The heterogeneous surface albedo was inconsistent with a global ocean, immediately prompting discussion over the fate of ethane, anticipated to be one of the most abundant products of the atmospheric photochemistry (Lunine et al. 1983). When Cassini–Huygens arrived in the Saturn system in 2004, a slew of fundamental

advances were enabled by the combined in situ and remote sensing observations over the next 13 yr. Newly identified features and processes prompted new questions, many of which will remain unanswered until a return mission to Titan (e.g., Nixon et al. 2018; Rodriguez 2021).

In light of these revelations—that Titan is an organic-rich ocean world where Earth-like geological processes rework the landscape and the complex atmospheric products that fall upon it—Titan was considered a target of high importance going into the 2012–2023 Decadal Survey (National Research Council 2011). Similar to the Titan Explorer study of 2007 (Lockwood et al. 2008; Lorenz et al. 2008a), the Titan Saturn System Mission concept study (TSSM) employed a comprehensive, three-pronged approach: an orbiter, a lander (targeting the lander to the northern lakes rather than the equatorial dunes),



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and a montgolfiere (Coustenis et al. 2009a; Reh 2009). This particular mission architecture was ultimately not put forward as the highest priority, instead deferred to the next decade “primarily because of the greater technical readiness of [the Europa flagship mission].” The Vision and Voyages report further noted that “[a Titan-returning mission’s] high scientific priority, however, is especially noteworthy” and thus recommended continued development of the technologies needed to support such a mission.

As the 2012–2023 decade unfolded, however, new technologies, scientific revelations, and congressional inertia motivated the addition of Titan and Enceladus to the New Frontiers 4 competition. With the selection of Dragonfly, some—but not all—of the high priority science identified by the TSSM will be addressed. Where, then, does Titan science stand now and what questions will be beyond the scope of Dragonfly? How is the exploration of Titan’s atmospheric, surface, and subsurface processes relevant to Ocean Worlds and other planets?

We discuss the answers to these questions as the community enters the purview of a new decadal survey, stemming from considerations submitted as a white paper by these same authors to the 2023–2032 National Academies Planetary Science and Astrobiology Decadal Survey. Starting with the atmosphere, we peel back the layers of Titan by first summarizing the state of knowledge. We then highlight pressing questions, and demonstrate how answering those questions provides important context for other worlds (be they ocean, terrestrial, or even beyond our solar system). Cognizant of the role of astrobiology in the scope of the coming decadal survey, we examine how interactions between these layers is little-understood but highly germane to studies of habitability, prebiotic chemistry, and the search for life. We end by elucidating the ample science opportunities that remain at Titan both in relation to and independent of Dragonfly.

2. Titan Is an Organic World

Titan hosts the most Earth-like atmosphere in the solar system. Similarities include the atmospheric structure (Fulchignoni et al. 2005; see our Figure 1), a nitrogen-dominated composition (95% N_2 , 4% CH_4 , and 1% trace species at the surface), and a surface pressure of 1.5 bar. The photolytic dissociation of atmospheric methane initiates a chain of photochemical reactions responsible for the plethora of organic species that make up the haze observed by Cassini–Huygens and ground-based facilities (Marten et al. 2002; Gurwell 2004; Ali et al. 2013; Cordiner et al. 2014, 2015, 2018; Cordier & Carrasco 2019; Molter et al. 2016; Desai et al. 2017; Lai et al. 2017; Palmer et al. 2017; Teanby et al. 2018; Lombardo et al. 2019; Thelen et al. 2019a, 2019b, 2020; Nixon et al. 2020). While unlike present-day Earth, Titan’s haze production offers insight into processes that may have taken place in Early Earth’s atmosphere (Trainer et al. 2006; Trainer 2013; Fleury et al. 2017; Hörst et al. 2018). The formation of organic hazes driven by photolytic destruction of methane is hypothesized as a source of prebiotic compounds and would shield the surface from excessive UV radiation (e.g., Sagan & Chyba 1997; Wolf & Toon 2010).

2.1. Pressing Questions and Future Investigations

Cassini identified the compositions of neutral and positive ions up to 99 Da (Waite et al. 2007; Wellbrock et al. 2013;

Woodson et al. 2015). Larger positive and negative ions with mass-to-charge ratio so large, for some, as to be similar to that of terrestrial proteins were also detected but could not be specifically identified due to the limitations of the Cassini instruments (Coates et al. 2007, 2009). The molecules resulting from Titan’s atmospheric chemistry molecules grow larger during polar winter and with decreasing altitude (Wellbrock et al. 2019), but their ultimate fate remains unknown. Thus, our current list of known compounds represents only the tip of the organic factory iceberg. Ongoing modeling efforts and laboratory experiments continue to investigate what reactions might be at work (Rannou et al. 2004; Waite et al. 2007; Vuitton et al. 2007, 2019; Krasnopolsky 2009, 2014; Nixon et al. 2012; Waite et al. 2013; Larson et al. 2014; Dobrijevic et al. 2014, 2016; Hickson et al. 2014; Lara et al. 2014; Loison et al. 2015, 2019; Luspai-Kuti et al. 2015; Wong et al. 2015; Sebree et al. 2016; Barth 2017; Douglas et al. 2018; Mukundan & Bhardwaj 2018; Berry et al. 2019; Bourgalais et al. 2019; Dubois et al. 2019a, 2019b, 2020) and to explore the properties of Titan haze analogs, tholins (Cable et al. 2012; Gautier et al. 2017; Sciamma-O’Brien et al. 2017; Hörst et al. 2018; Sebree et al. 2018). However, determining the dominant chemical pathways of Titan’s organic factory will require a more complete understanding of the chemical composition, abundance, and distribution of organic hazes in the atmosphere. Observations at different seasons in Titan’s year (29.5 Earth years) are critical, as monitoring with Cassini spanned only from the middle of northern winter to the very early summer (e.g., Teanby et al. 2019; Vinatier et al. 2012, 2020; Seignovert et al. 2021). Global atmospheric circulation in the upper atmosphere, which shows strong zonal prograde winds rapidly changing close to the northern summer solstice, has only been investigated very recently with ALMA (Lellouch et al. 2019; Cordiner et al. 2020). These wind changes also propagate in the middle atmosphere, as evidenced by CIRS data in the same period (Vinatier et al. 2020; Sharkey et al. 2021). Observations from an orbiter would be necessary to monitor interactions between the middle and upper atmospheric circulation as well as their potential couplings with atmospheric chemistry—all of which are currently poorly known.

Beyond chemical pathways, many questions remain or have arisen from Cassini–Huygens. How seasonal trends in condensate distributions extend to lower altitudes (Coates et al. 2007; Desai et al. 2017) and whether these affect sedimentation onto the surface remains unknown. Models indicate that microphysics plays an important role in cloud and haze formation (Barth 2017); increased understanding of the distribution, optical properties, and composition of hazes and clouds from observational (at Titan and ground-based; Jennings et al. 2012a, 2012b, 2015; Vinatier et al. 2012; Seignovert et al. 2017, 2021; Le Mouélic et al. 2018; West et al. 2018; Anderson et al. 2018b) and laboratory data (Anderson et al. 2018a; Nna-Mvondo et al. 2019; Mouzay et al. 2021) would constrain physical models (e.g., Loison et al. 2020). Several approaches to constrain the age of Titan’s atmosphere overlap at ~300–500 Myr, but whether this indicates the age of the atmosphere or ongoing methane photolysis is unclear (Hörst 2017). Replenishment from the interior offers a compelling solution to the methane loss, but more data are required to evaluate the likelihood of candidate mechanisms like clathrate dissociation and cryovolcanism (Lunine & Stevenson 1987; Tobie et al. 2006; Choukroun et al. 2010;

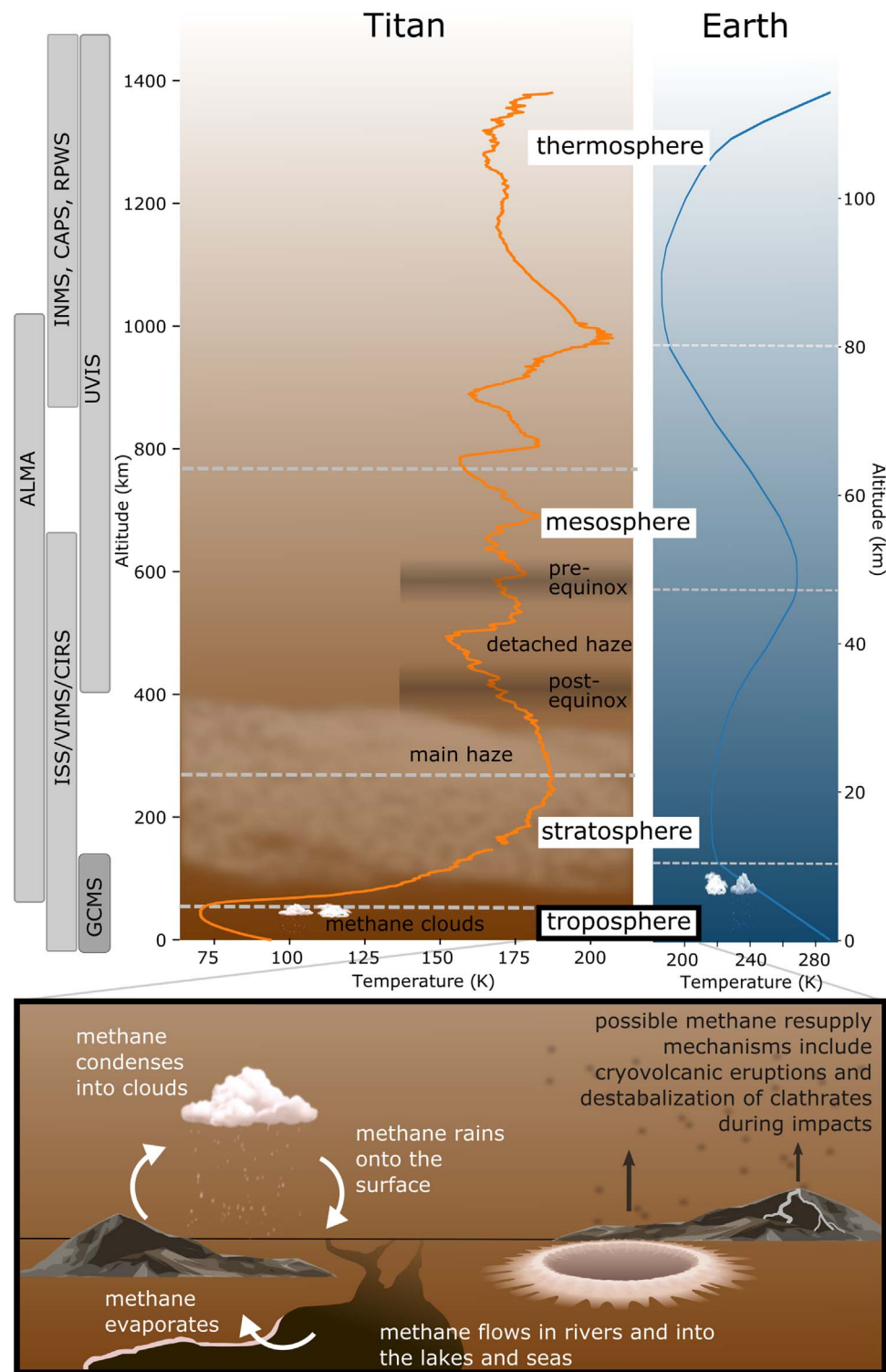


Figure 1. (Top) Comparison of the temperature profiles and structure of the atmospheres of Titan and Earth. Vertical bars on the left show the regions probed by Cassini instruments (Ion and Neutral Mass Spectrometer, INMS; Cassini Plasma Spectrometer, CAPS; Radio and Plasma Wave Science, RPWS; UltraViolet Imaging Spectrometer, UVIS; Imaging Science Subsystem, ISS; Visual and Infrared Mapping Spectrometer, VIMS; and Composite InfraRed Spectrometer, CIRS), the Huygens Gas Chromatograph Mass Spectrometer (GCMS), and the Atacama Large Millimeter/submillimeter Array (ALMA) telescope. (Bottom) Similar to the cycling of water on Earth, Titan's troposphere hosts the hydrological cycle of methane between the surface and the atmosphere. Irreversible loss of methane in the thermosphere suggests that a methane replenishment mechanism is necessary.

Choukroun & Sotin 2012; Sotin et al. 2012). Examples of necessary data include crustal dynamics, surface feature identification, isotopic fractionation, and a high-degree gravity field.

2.2. Role in an Ocean Worlds Program

Atmospheric organic species are the ultimate source of the organic sediments that dominate Titan's surface, so their formation and evolution in the atmosphere have important

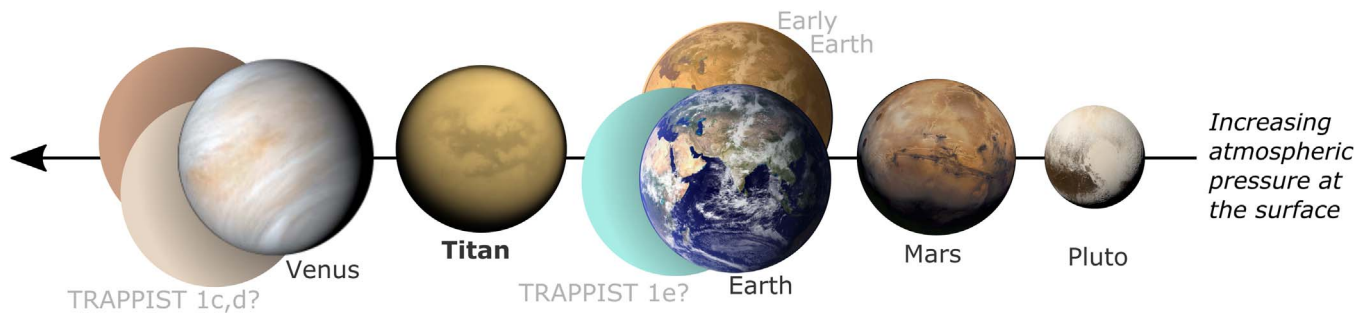


Figure 2. Titan's atmospheric density compared to that of terrestrial worlds both within and beyond (e.g., Morley et al. 2017) our solar system, highlighting the potential for comparative planetology between Titan and other worlds with atmospheres.

implications for surface geology and possible subsurface nutrient availability. Furthermore, investigating the processes that create complex species in Titan's atmosphere without, presumably, biological catalysts like those responsible for large molecules here on Earth offers fundamental insight into the chemistry that may precede or facilitate the rise of biochemistry on Early Earth (Trainer et al. 2006; Trainer 2013) and beyond. The study of Titan's atmospheric chemistry therefore offers crucial context for the habitability potential of other ocean worlds where the essential elements may be less abundant.

2.3. Relevance to Other Planets

Questions surrounding the dynamics and longevity of Titan's atmosphere link to questions about the gas and ice giants (Robinson et al. 2014; Toledo et al. 2019) and given the coupling between the atmosphere and surface about Earth, Venus, Mars, and Pluto (Mitchell et al. 2014; Mandt et al. 2015; Brain et al. 2016; Guendelman & Kaspi 2018; Read & Lebonnois 2018; Crismani et al. 2019; Köhn et al. 2019; Faulk et al. 2020; Kite et al. 2020; see our Figure 2). Without its own magnetic field, Titan's interactions with the solar wind and Saturn's magnetosphere offer the opportunity to explore whether magnetic fields are necessary for habitability. Moreover, Titan's atmosphere serves as a powerful backyard analog for hazy exoplanets from understanding the formation and evolution of atmospheric aerosols to how we might best detect and observe them as we have ground truth from both remote and in situ sensing (de Kok & Stam 2012; Forget & Leconte 2014; Tokano 2015; Arney et al. 2016; Checlair et al. 2016; Muñoz et al. 2017; He et al. 2017; Hörst et al. 2018; Levi & Cohen 2019; Lora et al. 2018; Alvarez Navarro et al. 2019; Martínez-Rodríguez et al. 2019; Miguel 2019).

3. Titan Is an Active Hydrological and Sedimentary World

Titan also has a methane-based hydrologic cycle akin to Earth's (Mitchell & Lora 2016; Hayes et al. 2018). The seasonal timing and magnitude of surface-atmosphere fluxes of methane, including observed clouds and rainstorms (Turtle et al. 2009, 2011a, 2011b, 2018; Brown et al. 2010; Barnes et al. 2013; Lemmon et al. 2019; Dhingra et al. 2019), are probably linked to existing surface and subsurface liquid reservoirs (Mitchell 2008; Tokano 2009; Lora & Mitchell 2015; Lora et al. 2015, 2019; Mitchell & Lora 2016; Newman et al. 2016; Faulk et al. 2017, 2020; Tokano & Lorenz 2019; Tokano 2020). The hydrological cycle shapes the surface, producing landforms that bear a striking resemblance to those found on Earth (Hayes 2016) (Figure 3). Lakes and seas of

liquid methane and ethane (Brown et al. 2008; Mastrogiuseppe et al. 2014, 2016, 2018) up to hundreds of meters deep (Mastrogiuseppe et al. 2014, 2016, 2018; Stofan et al. 2007) are found across Titan's polar regions (Turtle et al. 2011b; Sotin et al. 2012; Barnes et al. 2013; Dhingra et al. 2019; Barnes et al. 2015; Hofgartner et al. 2014, 2016; Cornet et al. 2015; MacKenzie et al. 2019b; Solomonidou et al. 2020a). River channels and rounded cobbles imaged by Huygens (Karkoschka & Schröder 2016) and the radar-bright channels (Barnes et al. 2007; Lorenz et al. 2008b; Burr et al. 2009, 2013; Le Gall et al. 2010; Cartwright et al. 2011; Black et al. 2012; Langhans et al. 2013) and fans (Birch et al. 2016; Radebaugh et al. 2018; Cartwright & Burr 2017) observed by Cassini (Wasiak et al. 2013; Poggiali et al. 2016) demonstrate that Titan's hydrologic cycle is intimately connected with the sedimentary cycle: complex organic compounds synthesized and advected in and by the atmosphere are further transported and modified across the surface by the only known active extraterrestrial hydrologic cycle. Perhaps the best studied sediments on Titan are the organic sands that occupy 17% of the moon's surface (Soderblom et al. 2007; Barnes et al. 2008; Bonnefoy et al. 2016; Le Gall et al. 2011, 2014; Rodriguez et al. 2014; Brossier et al. 2018). Linear dunes (hundreds of kilometers long and ~100 m in height) demonstrate the importance of aeolian processes and underlying topography in the redistribution of Titan's organics (Radebaugh et al. 2008, 2010; Lorenz & Radebaugh 2009; Rodriguez et al. 2014; Malaska et al. 2016b; Paillou et al. 2016; Telfer et al. 2019). Titan's vast mid-latitude plains (~65% of the surface) are also hypothesized to consist of organic materials (Malaska et al. 2016a; Lopes et al. 2016, 2020; Solomonidou et al. 2018; MacKenzie et al. 2019a), but their composition and origin remain unknown.

3.1. Pressing Questions and Future Investigations

Despite advances in our understanding of the landscapes of Titan, the composition of the surface remains ill-constrained. Cassini observations, limited in spectral and spatial resolution, suggest two general categories of materials: organic-rich and water-ice rich (Barnes et al. 2008; Soderblom et al. 2009; Rodriguez et al. 2014; Brossier et al. 2018; Solomonidou et al. 2018; Griffith et al. 2019). Continued laboratory and theoretical work into the possible compositions and physical properties of Titan's solid (Méndez Harper et al. 2017; Cable et al. 2018, 2019, 2020; Maynard-Casely et al. 2018; Yu et al. 2018, 2020) and liquid (e.g., Farnsworth et al. 2019; Hanley et al. 2020; Engle et al. 2020; Steckloff et al. 2020; Vu et al. 2020) surface materials are crucial for informing interpretations

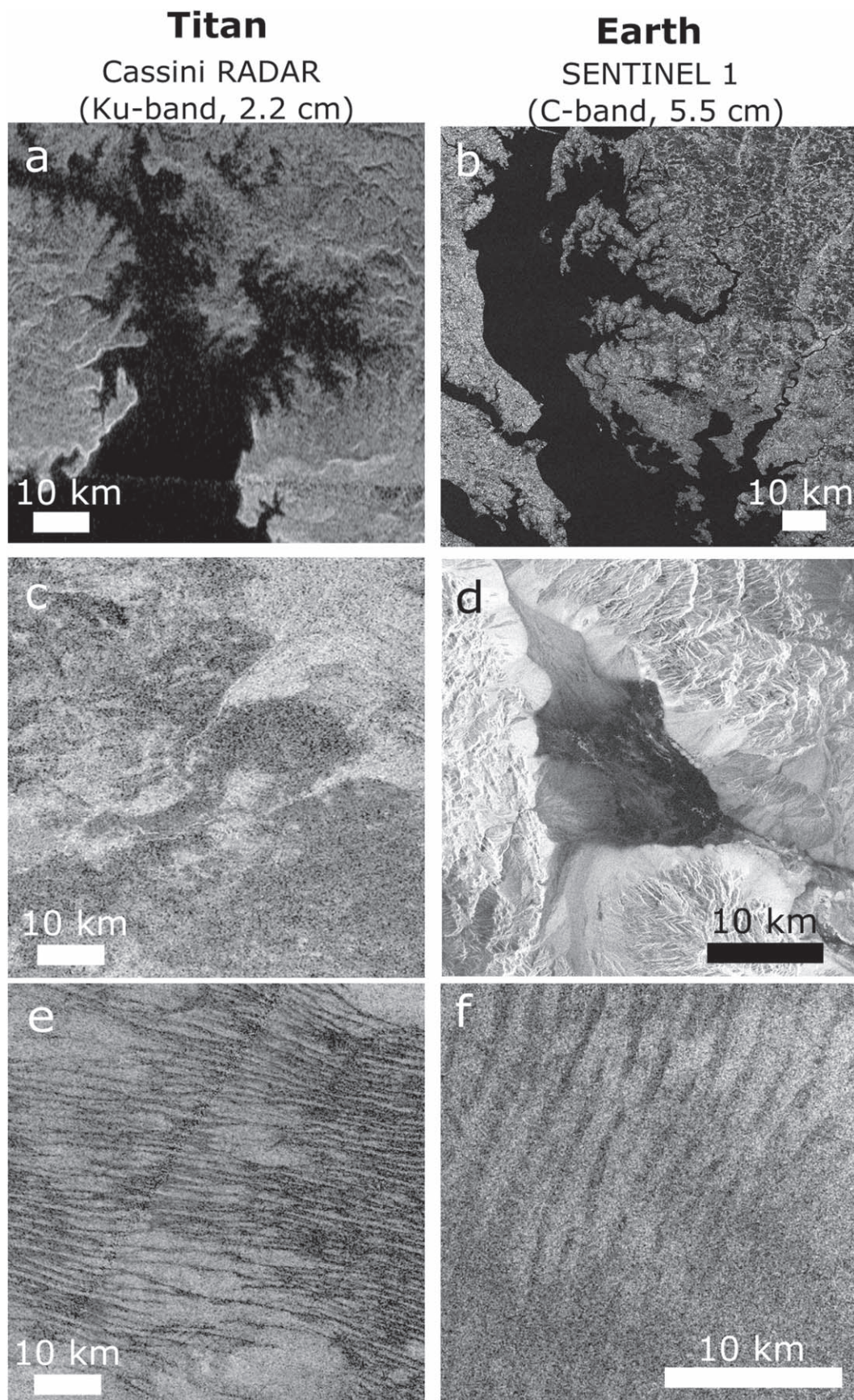


Figure 3. Select examples of terrains shaped by Titan's hydrological and sedimentological processes as viewed by Cassini RADAR and terrestrial analogs observed by SENTINEL 1: (a) shorelines of Kraken Mare from T28; (b) Chesapeake Bay (38.884°N, 76.398°W); (c) river channels terminating in fans from Ta; (d) Death Valley channels and fans (36.688°N, 117.177°W); (e) organic sands organized into dunes from T49; and (f) Namibian longitudinal dunes (24.285°S, 15.437°E).

of Cassini–Huygens data and supporting future exploration of the surface like the Dragonfly mission.

Dramatic advances in our understanding of Titan’s seasonally evolving weather and climate (Mitchell et al. 2006; Mitchell & Lora 2016; Hayes et al. 2018) are similarly accompanied by new questions and key unknowns. The principal mechanisms controlling the timing and distribution of humidity (Ádámkovics et al. 2016; Ádámkovics & de Pater 2017; Lora & Ádámkovics 2017), convection, methane cloud formation, and precipitation remain incompletely understood, as do the sources and sinks of atmospheric methane and the roles of atmospheric variability (Griffith et al. 2008; Mitchell et al. 2009; Roe 2012; Mitchell & Lora 2016; Hayes et al. 2018) and transient phenomena like dust storms (Rodríguez et al. 2018) in the climate. Likewise, the impact of heterogeneous surface-atmosphere coupling, for example, how Titan’s lakes affect the north polar environment (Rafkin & Soto 2020) and the magnitude and importance of regional climate variability are still largely unexplored. Further observations of Titan’s weather phenomena, coupled with improvements in physical modeling, are needed to continue elucidating Titan’s climate system and to link synoptic-scale processes to those at global and interannual scales, as well as to their impacts on the surface.

Global, high-resolution imaging (<100 m) would revolutionize our understanding of Titan’s landforms, how they interact with each other and the atmosphere, and how they have evolved in the same way that Mars Global Surveyor’s orbital campaign fundamentally changed the study of Mars. Similarly, the lack of knowledge of Titan’s topography specifically limits the study of the transport of liquids and sediments on the surface, as well as of the influence of the surface on the atmosphere. Cassini data covers only 9% of Titan at scales too coarse for detailed geophysical and hydrological analysis of hydrologic catchments, mountain wave effects, or orographic clouds and precipitation (Corlies et al. 2017). Huygens data offer higher resolution but only over a few square kilometers (Daudon et al. 2020). In conjunction with maps of surface composition at high spatial and spectral resolution, global imaging and topographic data would address fundamental questions surrounding the hydrological, sedimentological, and meteorological cycles of Titan, augmenting Cassini data and complementing Dragonfly’s planned local in situ investigations.

3.2. Role in an Ocean Worlds Program

Titan represents the organic-rich endmember of the Ocean World spectrum (Figure 4). Understanding the surface and atmospheric processes that create, modify, and transport these materials on Titan, and the timescales and volumes on which they act, would elucidate the role these processes play in planetary habitability and their significance.

3.3. Relevance to Other Planets

Titan’s surface and climate system serves as a natural laboratory for studying the fundamentals of a planetary-scale hydrologic cycle, offering the unique opportunity to observe how this cycle controls the physical and chemical evolution of the landscape in an environment akin to but less complex than

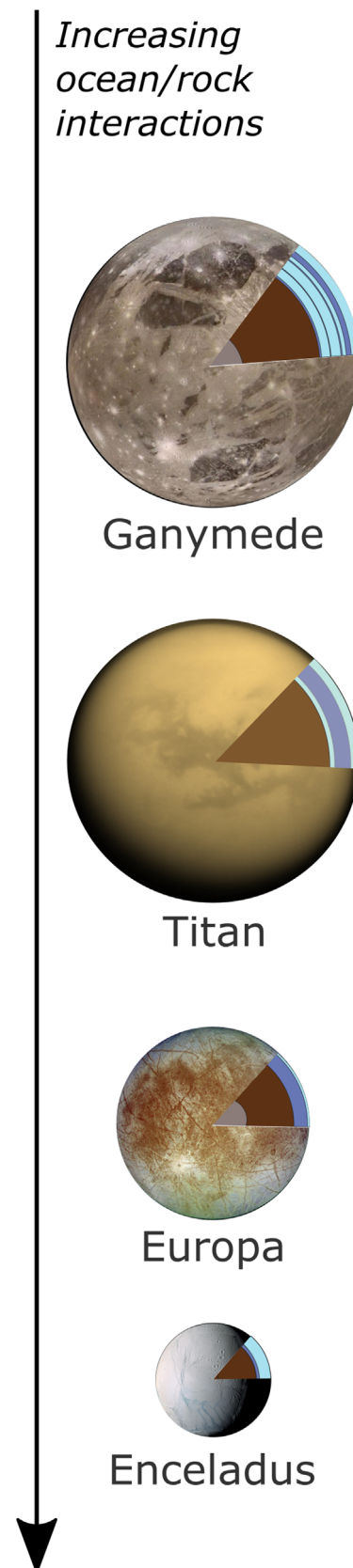


Figure 4. Titan on the water-rock interaction spectrum of Ocean Worlds, as anticipated from models of interior structure (insets, based on the work of Vance et al. 2018).

Earth's. For example, sea level rise is likely ongoing and has dramatically shaped the coasts of Titan's large seas (Aharonson et al. 2009; Hayes et al. 2011, 2017; Lora et al. 2014; MacKenzie et al. 2014, 2019b; Birch et al. 2018; Tokano & Lorenz 2019; Tokano 2020), and is likely ongoing although the rates remain loosely constrained; study of Titan's coasts and ongoing erosional/depositional processes could be directly compared to the rapid changes on Earth and inform the study of paleo coastlines on Mars.

4. Titan Is an Ocean World

A subsurface water ocean lies beneath Titan's organic-covered ice crust (Nimmo & Pappalardo 2016), evidence for which includes gravitational tides (Iess et al. 2012; Mitri et al. 2014) and larger-than-expected obliquity (Baland et al. 2011, 2014). For a detailed review of the post-Cassini understanding of Titan's interior, see Sotin et al. (2021).

4.1. Pressing Questions and Future Investigations

The thickness of Titan's crust is loosely constrained to 50–200 km (Choukroun & Sotin 2012; Nimmo & Pappalardo 2016; Hemingway et al. 2013; Lefevre et al. 2014) and the extent and duration of convection within the ice crust (Hemingway et al. 2013; Lefevre et al. 2014; Noguchi & Okuchi 2020) is still debated. Estimates of the oceanic depth span 500–700 km (Castillo-Rogez & Lunine 2010; Iess et al. 2012; Gao & Stevenson 2013; Chen et al. 2014) and the state of differentiation in the core is unknown (Nimmo & Pappalardo 2016; Baland et al. 2014; Gao & Stevenson 2013; O'Rourke & Stevenson 2014). The presence of salts or ammonia may explain the ocean's high density (Mitri et al. 2014; Leitner & Lunine 2019), but magnesium sulfate is also a potential solution (Vance et al. 2018). Primordial icy bodies provided noble gases and organic matter during Titan's accretion, making the interior an even vaster source of organics than the atmosphere, with some models predicting $1000\times$ the current atmospheric methane abundance (Tobie et al. 2012). These considerations, coupled with detection of radiogenic ^{40}Ar by Huygens (Niemann et al. 2005) suggest that outgassing from the interior may be responsible for the atmosphere. New isotopic measurements of noble gases and methane are necessary to resolve key questions concerning the ocean composition, the evolution of the interior and atmosphere, and the formation of Titan (Glein 2015, 2017; Marounina et al. 2015, 2018; Miller et al. 2019; Journaux et al. 2020a).

At pressures >500 MPa, a layer of high-pressure ice may separate Titan's core from the ocean (Vance et al. 2018), but if the heat flux is high enough and/or salinity are high enough, the ocean may be in direct contact with the silicate core (Journaux et al. 2020b). Initially, the presence of high-pressure ice prompted the oceans of the largest icy satellites to be deemed inhospitable, assuming that separation by ice precluded exchange between the ocean and core. However, advances in our knowledge of how ices behave at high pressure show that convection can move material through the ice layer (Choblet et al. 2017; Kalousová et al. 2018), including salts and volatiles like ^{40}Ar (Journaux et al. 2017; Kalousová & Sotin 2018). More laboratory and theoretical investigations into the properties of high-pressure ices and hydrates are needed before we fully understand their implications for Ocean World habitability.

4.2. Role in an Ocean Worlds Program

Determining whether Titan's ocean is in contact with the rocky core would provide a key constraint to the formation and longevity of large Ocean Worlds both within and beyond our solar system (Journaux et al. 2013). Studying the very origins of Titan's organic cycle—from the primordial to hydrothermally altered material—informs our understanding of the role of volatile-rich ices in the early solar system.

5. Is Titan a Habitable World?

The search for life elsewhere in the universe logically employs the guide of the biochemical foundations of Earth's biosphere, giving rise to the classical conditions necessary for habitability: liquid water, essential elements (CHNO; the availabilities of P and S are yet to be determined), and energy sources (Hoehler 2007; Shock & Holland 2007; Domagal-Goldman et al. 2016). All three factors exist on Titan. The question is where they have been or may be collocated and for how long.

5.1. Pressing Questions and Future Investigations

Titan's deep crustal ice and subsurface ocean could be one of the largest habitable realms in the solar system, with a volume of liquid water 18 times that of the Earth's oceans and CHNOPS potentially available from primordial and/or thermally processed materials (Miller et al. 2019). Tectonic activity and cryovolcanism may facilitate the delivery of surface organics through the crust. Whether any or all of these processes are at work and on what timescales they operate on Titan remain open questions, with implications for other ocean worlds where habitability may rely even more heavily upon the exchange of surface and subsurface material. For example, temperature and pressure conditions at the putative depth of Titan's stagnant lid/convective ice transition are very similar to those encountered within terrestrial deep glacial ice, which hosts a diversity of microbial life (Miteva et al. 2009) in the intergrain channels between solid ice grains (Price 2007; Barletta & Roe 2012). In these intergrain regions, microbial metabolism is slow enough that the environment may be habitable for 10,000 years only a few orders of magnitude lower than Titan's hypothesized convective cycle.

A frigid ambient temperature of ~ 90 K (Jennings et al. 2009, 2011, 2016, 2019; Cottini et al. 2012) makes Titan's surface largely inhospitable for Earth-like life using water as the biochemical solvent. However, there are ephemeral scenarios in which liquid water is present at Titan's surface: lavas erupting from cryovolcanoes and impact-generated melt. While some geomorphological evidence supports the existence of cryovolcanism (Lopes et al. 2007, 2013, 2020), its mechanics (Mitri et al. 2008; Moore & Pappalardo 2011) are not well understood, in part due to the lack of constraints on the extent, makeup, and activity of the crust as well as the ocean composition. However, impact craters are found across Titan's surface (Lorenz et al. 2007; Le Mouélic et al. 2018; Soderblom et al. 2010; Neish & Lorenz 2012; Neish et al. 2013; Neish & Lorenz 2014; Neish et al. 2016; Werynski et al. 2019; Hedgepeth et al. 2020; Solomonidou et al. 2020b). During the impact, crustal material and surface organics mix; the resulting pockets of liquid water eventually freeze on time-scales loosely constrained to up to tens of thousands of years (Artemieva & Lunine 2003, 2005; O'Brien et al. 2005;

Neish et al. 2006; Davies et al. 2010, 2016). Mixing tholins with liquid water in the laboratory produces amino acids on a timescale of days (Neish et al. 2008, 2009, 2010, 2018). Titan's transient liquid water environments are thus extraterrestrial laboratories for exploring how far prebiotic chemistry can progress under time and energy constraints that are difficult to realistically reproduce experimentally (Neish et al. 2018). The Dragonfly mission will take advantage of this opportunity with surface composition measurements near a large impact crater.

Without an understanding of the chemical processes necessary for the emergence of life, it is impossible to say with certainty how long it takes for life to arise (Orgel 1998). This timescale is a critical unknown in our concept of habitability: is there a minimum time necessary for all the key ingredients to be collocated? The answer to this question has immediate implications for strategizing the search for life elsewhere (both where to search and whether to target extant or extinct life), especially since the lifetime of the liquid oceans on both confirmed and candidate ocean worlds remains an active area of research (Nimmo & Pappalardo 2016; Neveu & Rhoden 2019). Any constraints on habitability timescales from Titan's transient liquid water environments would provide key context for exploration of potentially habitable environments and the search for life.

Finally, Titan's lakes and seas of liquid hydrocarbons offer a unique opportunity to investigate whether the solvent necessary for biochemistry must be water. Theoretical considerations suggest alternative chemistries are possible (Benner et al. 2004; Lv et al. 2017) and the abundance of solid and liquid organic molecules available on the surface and lack of UV radiation make the surface of Titan an advantageous place for exploring the possibility of a true second genesis (Lunine & Lorenz 2009; Lunine 2010; McKay 2016). Theoretical investigations are exploring both the possibilities for lipid membrane-like structures in low temperature environments and whether cell membranes are even necessary (Stevenson et al. 2015; Rahm et al. 2016; Palmer et al. 2017; Sandström & Rahm 2020). Laboratory and theoretical models are revolutionizing our understanding of the possible conditions within Titan's lakes and seas (Cordier & Carrasco 2019; Luspai-Kuti et al. 2015; Cordier et al. 2012, 2016, 2017; Cordier & Liger-Belair 2018; Hodyss et al. 2013; Corrales et al. 2017; Malaska et al. 2017; Hartwig et al. 2018; Czapinski et al. 2019, 2020; Farnsworth et al. 2019). Employing these new findings to constrain the habitability potential of Titan's liquid hydrocarbons requires both determining the composition of Titan sediments as the Dragonfly mission's plans to do by exploring at a portion of one of Titan's low-latitude dune fields and monitoring the composition, physical conditions, and seasonal evolution of Titan's polar lakes and seas with future missions.

6. Future Investigations at Titan

6.1. Dragonfly

Dragonfly, the next New Frontiers (NF) mission, is a relocatable lander, to explore the prebiotic chemistry of Titan's surface (Turtle et al. 2017; Lorenz et al. 2018a). (For a detailed description of Dragonfly's science goals and objectives, see Barnes et al. 2021.) Arriving in the 2030s, Dragonfly will resolve a critical unknown: the chemical composition of Titan's solid sediments. By using a mass spectrometer to measure compositions of the organic-rich sands of the equatorial dune

fields, water-ice rich clasts from the relatively unaltered interdunes, and previously melted impact melt ejecta from an impact crater, Dragonfly will begin to answer the question of how far prebiotic chemistry can progress in environments that provide long-term access to key ingredients for life, thereby providing crucial context for astrobiological investigations across the solar system. Dragonfly will also determine elemental abundances in the near subsurface beneath the lander with a gamma-ray neutron spectrometer, thus informing the availability and distribution of elements key to habitability.

Sample provenance both at the scale of Dragonfly's immediate environs and the local region is essential to interpreting the chemical findings in context. Dragonfly is thus equipped with a suite of cameras to conduct imaging campaigns at local, nested scales. Meteorological and geophysical instruments will determine aeolian transport rates and monitor local weather conditions, as well as probe the thermal and electrical properties of the surface. Geophones and a seismometer round out the contextual measurements by probing the dynamics and properties of the ice crust, potentially constraining the depth to the ocean (Stähler et al. 2018).

Dragonfly's payload is thus poised to revolutionize not only our understanding of Titan's chemistry and geology but address more broadly how far prebiotic chemistry can progress and what chemical and geological processes make a planet or moon habitable. But, just as Curiosity addresses different fundamental science than the Mars Reconnaissance Orbiter, the NF-scope and architectural choices that make Dragonfly best suited for its local in situ investigation necessarily preclude addressing many other outstanding questions at Titan, especially those requiring a global perspective.

6.2. Other Future Missions

Thus, as demonstrated by exploration of Mars, a sequence of opportunities is needed to build upon and sufficiently leverage the detailed exploration of Titan begun by Cassini-Huygens and to be continued by Dragonfly in the coming decades. In particular, exploring the polar lakes and seas, their influence on Titan's global hydrologic cycle, and their potential habitability, will remain out of even Dragonfly's impressive range. Such measurements would also be complemented by orbital imaging at higher spatial and temporal resolutions than what Cassini or ground-based observations could provide. A higher order gravity field would reveal eroded craters and thus constrain the prevalence of transient liquid water environments. More specifically, Dragonfly's seismic investigation of the interior would be significantly enhanced by a global topographic data set and higher fidelity mapping of the gravity field.

Further study of the dynamics of Titan's climate and the seasonal evolution of hazes and weather phenomena (e.g., clouds and haboobs, Smith et al. 2016; West et al. 2016; Le Mouélic et al. 2018; Rodriguez et al. 2018; Stähler et al. 2018; Vinatier et al. 2018; Lemmon et al. 2019) requires continued long-term monitoring with ground- and space-based assets as Titan's northern summer unfolds. A global imaging data set would facilitate understanding the beginning-to-end life cycle of the materials sampled by Dragonfly. Furthermore, as new species are identified in Titan's atmosphere, such as with ALMA (Figure 5), the needs of Titan exploration evolve. For example, as some of these species are only detected above 300 km and thus require orbital monitoring since low vapor

Molecules Detected in Titan's Atmosphere by Remote Sensing

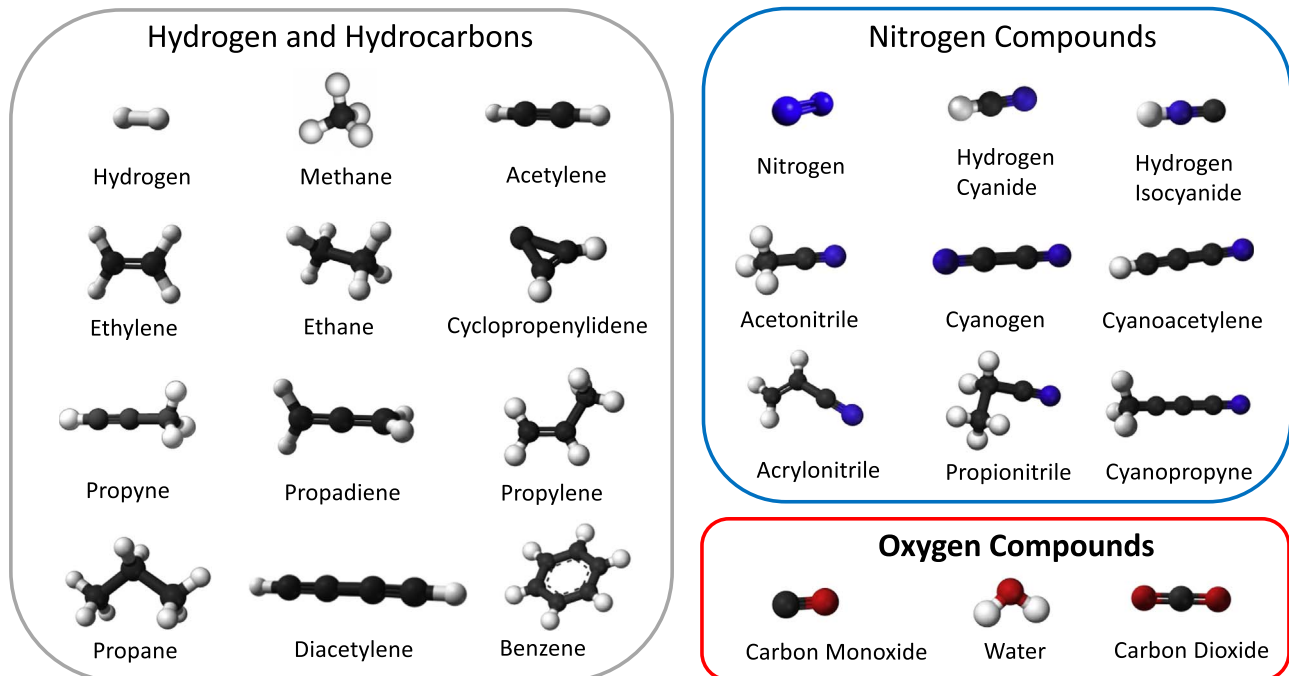


Figure 5. Molecules in Titan's atmosphere that have been uniquely identified via remote sensing. (Molecule image credit: Ben Mills/Wikimedia Commons).

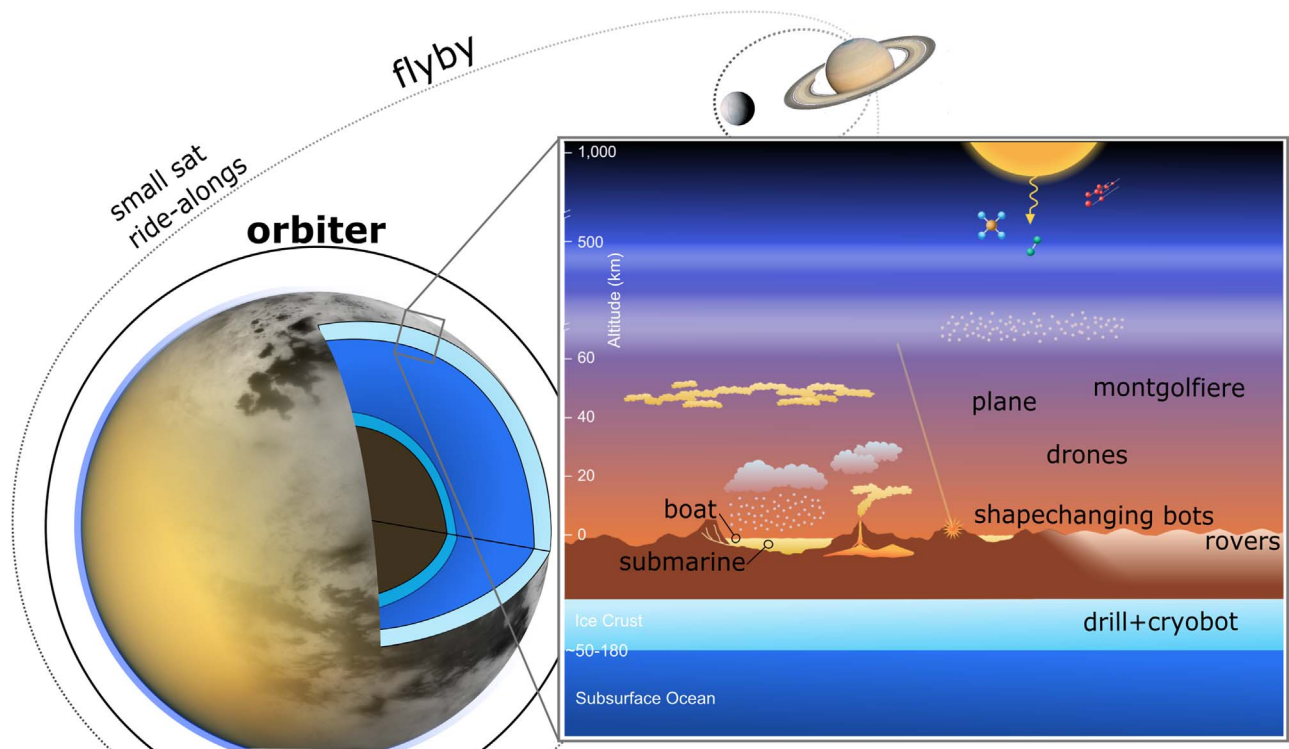


Figure 6. Some possible architectures for returning to Titan. The options are as varied as the moon's landscape. Inset modified from the Titan Explorer Mission Report.

pressures in the troposphere would make detection difficult for Dragonfly.

At least two examples for how to manifest these complementary investigations in the next decade were described in white papers to the 2023–2032 National Academies Planetary Science and Astrobiology Decadal Survey, representing New

Frontiers and Flagship-scope efforts. But these are far from a comprehensive representation of possible architectures for returning to Titan (Figure 6). A return to the Saturn system could orbit Titan (Sotin et al. 2017) for global mapping and geophysics or leverage the proximity of two prime Ocean World targets to jointly explore both Enceladus and Titan, via

orbiting Saturn with plume flythroughs and frequent Titan flybys (Coustenis et al. 2009b; Sotin et al. 2011) or shuttling between Titan and Enceladus (Russell & Strange 2009; Sulaiman 2021). Titan's thick atmosphere can be leveraged for long-duration flight (Lorenz 2008; Barnes et al. 2012; Ross et al. 2016) at altitudes high enough to maximize areal coverage and minimize atmospheric interference on compositional surface mapping (e.g., Corlies et al. 2021). Ride-along small satellites can be exploited for gravity science (Tortora et al. 2018). On the surface, the diversity of interesting terrains inspired the study of a fleet of shape-changing robots (Tagliabue et al. 2020), a fleet of mini-drones, and a drone capable of also floating on the surface of the seas (Rodríguez 2021). A mission to float on Titan's seas has been proposed (Stofan et al. 2013) and submerged instrumentation and/or vessels have been studied (e.g., Lorenz et al. 2016, 2018b). These in situ elements would benefit and/or require an orbiter for data relay. The diversity of mission concepts (and combinations thereof) that have been proposed and studied reflect the diversity of science questions left to answer at Titan and, importantly, demonstrate that compelling architectures span the full spectrum of NASA and ESA mission classes.

7. Titan Is an Unparalleled Destination

Titan offers the opportunity to study a myriad of fundamental planetary science questions. The processes that govern its atmosphere, surface, and interior and interactions between these three environments make Titan an analog for destinations across the solar system and beyond. In the next decade, Dragonfly will continue the legacy of Cassini-Huygens and radically transform our understanding of Titan's chemistry, geology, and astrobiological potential. But if the last decade has taught us anything, it is that this moon's complexity tends to defy our imagination. There is still much left to learn before we fully understand Saturn's largest moon, requiring mission opportunities in addition to Dragonfly in the next decade.

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