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The exploration of Titan with an orbiter and a lake probe

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ABSTRACT

Fundamental questions involving the origin, evolution, and history of both Titan and the broader Saturnian system can be answered by exploring this satellite from an orbiter and also *in situ*. We present the science case for an exploration of Titan and one of its lakes from a dedicated orbiter and a lake probe. Observations from an orbit-platform can improve our understanding of Titan's geological processes, surface composition and atmospheric properties. Further, combined measurements of the gravity field, rotational dynamics and electromagnetic field can expand our understanding of the interior and evolution of Titan. An *in situ* exploration of Titan's lakes provides an unprecedented opportunity to understand the hydrocarbon cycle, investigate a natural laboratory for prebiotic chemistry and habitability potential, and study meteorological and marine processes in an exotic environment. We briefly discuss possible mission scenarios for a future exploration of Titan with an orbiter and a lake probe.

1. Introduction

Titan, Saturn's largest satellite, is a unique object in the Solar System, having a substantial nitrogen atmosphere, a surface with a complex interplay of geological processes (Lopes et al., 2010) and an outer ice shell overlying a subsurface ocean (Iess et al., 2012; Mitri et al., 2014). The climate on this icy satellite boasts a multi-phase alcanological cycle where methane plays a role similar to water on Earth. The Cassini–Huygens mission to the Saturn system, which is still ongoing after 10 years of operations, accomplished a first in-depth exploration of Titan (Lebreton et al., 2009; Coustenis et al., 2009a). The data revealed hydrocarbon lakes and seas located mostly in Titan's polar regions (Stofan et al., 2007; Hayes et al., 2008), which, combined with extensive equatorial dune deposits (Lorenz et al., 2006), form a major reservoir of organics in the Solar System. The presence of standing bodies of liquid, dissected fluvial channels (Lopes et al., 2010), tectonic features (Radebaugh et al., 2007; Mitri et al., 2010), vast dune fields (Lorenz et al., 2006) and putative cryovolcanic flows (Lopes et al., 2007; 2013) shows striking analogies with terrestrial

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geological activity. Titan is the only other place in the Solar System, with the Earth, to have exposed lakes and seas, albeit with different materials.

The initial discoveries of the Cassini–Huygens mission inspired an extension of the mission in 2008, first as the Cassini Equinox Mission and then as the Cassini Solstice Mission to 2017, as well as multiple proposals to return to the Saturnian system for further exploration of this enigmatic satellite. Two mission proposals, Titan and Enceladus Mission TandEM (Coustenis et al., 2009a) and Titan Explorer (Lorenz, 2009) for ESA and NASA respectively, merged to form the Titan Saturn System Mission TSSM (Coustenis et al., 2010; ESA, 2009) which sought further exploration of Titan with both a dedicated orbiter and *in situ* probes (balloon and lake probe) and a large instrument suite. Ultimately ESA and NASA decided to prioritize the Europa Jupiter System Mission (EJSM), which would later become ESA's first Large (L) L1 mission of its Cosmic Vision Program (2015–2025), the JUpiter ICy moon Explorer (JUICE) with a planned launch date of 2022 (Grasset et al., 2012). The demise of TSSM inspired mission proposals smaller in scale and cost including the Titan Mare Explorer TiME (Stofan et al., 2010, 2013), the Titan Aerial Explorer TAE (Lunine et al., 2011) and the Journey to Enceladus and Titan JET (Sotin et al., 2011), using either a probe or an orbiter but not both, and a small instrument suite. Building on this heritage, the exploration of Titan with an orbiter and a lake probe was presented as a White Paper in response to the 2013 European Space Agency (ESA)'s Call for Science Themes for the Large-class (L) L2 and L3 missions (Mitri et al., 2013). This paper is based upon the fore-mentioned White Paper. The Online Supplementary material for this paper includes the list of the authors and the supporters of the White Paper from the scientific community.

Future exploration of Titan with a dedicated orbiter and an *in situ* lake probe would address central themes regarding the nature and evolution of this icy satellite and its organic-rich environment. While the term lake probe is used in this paper and in previous literature, it should be noted that the ideal target of any future exploration of the standing liquid bodies on Titan would mostly likely be one of the large seas found in the north polar region rather than a lake. Bodies of standing liquid on Titan with large dimensions are classified as seas (mare) rather than lakes (lacus). Prior to an orbiter phase around Titan and an *in situ* exploration of its lakes, mission scenarios could also involve investigations of the planet Saturn and its other satellites including the geologically active icy moon Enceladus. A companion White Paper proposed the exploration of Enceladus with flybys and Titan with an orbiter and a balloon probe (Tobie et al., 2014). While the exploration of the Saturn system and its moons, Enceladus and Titan, was ultimately not selected for the L2 and L3 missions, the scientific case for such exploration received strong support from the scientific community (Mitri et al., 2013; Tobie et al., 2014).

Section 2 summarizes the scientific objectives for Titan's exploration and how future scientific investigations of Titan with a dedicated orbiter and lake probe can address some of these objectives. In Section 3 we discuss how *in situ* exploration of Titan's lakes can provide an unprecedented opportunity to understand the hydrocarbon cycle, investigate a natural laboratory for prebiotic chemistry and the limits of life, and study meteorological and marine processes in an exotic environment. In Section 4 we present the scientific investigations, measurements and example approaches. Finally, in Section 5 we review the mission concept legacy and in Section 6 we present a mission scenario for the future exploration of Titan with an orbiter and a lake probe.

2. Scientific objectives and investigations for a future exploration of Titan

In spite of all its advances, the Cassini–Huygens mission, due to its limited instrumentation and timeline, among other things, cannot address some fundamental questions regarding Titan such as (1) What are the complex organic molecules that form the dune material, and how have they been formed? (2) What is the composition of the lakes and seas? (3) What are the processes that form and maintain the atmosphere? and (4) Is Titan endogenically active? In fact, these central themes can be investigated by a future mission using an orbiter and a lake probe.

To answer these questions among others, the scientific objectives for a future exploration of Titan include (Table 1) (i) Determine how Titan was formed and evolved, and its internal structure (Goal 1); (ii) Determine the nature of the geological activity on Titan (Goal 2); (iii) Characterize the atmosphere of Titan and determine how the alcanonological cycle works (Goal 3); and (iv) Determine the marine processes and chemistry of Titan's lakes and seas (Goal 4).

2.1. Geophysics

The combination of measurements of the gravity field, rotational dynamics and electromagnetic field will contribute to the achievement of the scientific objective Goal 1 (Table 1). Static and dynamic gravity field measurements (Iess et al., 2010, 2012), and shape models (Zebker et al., 2009; Mitri et al., 2014) from the Cassini–Huygens mission have greatly expanded our knowledge of the geophysical processes and structure of Titan's interior and as a consequence its formation and evolution have also become better understood. Data from the Cassini–Huygens mission suggest that either Titan has no induced magnetic field or else it is not yet detectable, while an intrinsic magnetic field is found to be absent (Wei et al., 2010). While there is still not yet a unique internal structural model of Titan, constraints provided by gravity, topography and rotation data suggest that Titan's interior has some degree of differentiation and possesses a water-ice outer shell separated from its deep interior by a dense subsurface water ocean (Mitri et al., 2014). Thermal models suggest the presence of a high-pressure polymorph ice layer between the deep interior and the subsurface ocean (Tobie et al., 2005; Mitri and Showman, 2008; Mitri et al., 2010).

Radio-tracking data registered during multi-flybys of Titan has yielded gravity field measurements with a spherical harmonic expansion to degree-3 (Iess et al., 2010, 2012). The quadrupole (J_2 and C_{22}) moments of the gravity field were used to constrain the normalized axial moment of inertia which value was inferred

Table 1
Scientific objectives for a future exploration of Titan.

Goal 1	Determine how Titan was formed and evolved, and its internal structure
Goal 2	Determine the nature of the geological activity of Titan
Goal 3	Characterize the atmosphere of Titan and determine how the alcanological cycle works
Goal 4	Determine the marine processes and chemistry of Titan's lakes and seas