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Astraeus: Exploring Titan's lakes, surface, and atmosphere

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Abstract

Titan, Saturn's largest moon, supports a dense atmosphere, numerous bodies of liquid on its surface, and as a richly organic world is a primary focus for understanding the processes that support the development of life. In-situ exploration of the body's equatorial regions, something begun by the Huygens lander in the early 2000s, is soon set to continue with the upcoming Dragonfly quadcopter. This commitment of NASA to flying on the body marks a bold step towards more adventurous mission architectures, and following the mission's completion, numerous other opportunities will be available where mission designers can go further and leverage hundreds of years of human experience traversing surface, atmosphere and liquid on Earth to begin the first in-situ exploration of Titan's polar lakes. This mission offers a distributed architecture across Titan's orbit, upper atmosphere, near surface atmosphere, and surface lakes.
Keywords: Titan, CubeSat, Orbiter, Lander, Submarine.

1. Introduction

Titan, Saturn's largest moon, supports a dense atmosphere, numerous bodies of liquid on its surface, and as a richly organic world is a primary focus for understanding the processes that support the development of life [1].

In-situ exploration of the body's equatorial regions, something begun by the Huygens lander in the early 2000s, is soon set to continue with the upcoming Dragonfly quadcopter. This commitment of NASA to flying on the body marks a bold step towards more adventurous mission architectures, and following the mission's completion, numerous other opportunities will be available where mission designers can go further and leverage hundreds of years of human experience traversing through atmosphere and liquid on Earth to continue the exploration of Titan on a wider scale and begining the first in-situ exploration of Titan's lakes.

Some work on this project has been presented previously; specifically on numerical studies of lake dynamics in the context of an example bioinspired spacecraft, analogous to a robotic diving gannet seabird [1]. Now, however, a larger mission design team are involved in revisiting the conclusions of the previous study and considering a wider range of mission profiles that can access more of Titan's distinct and intruiging environments. As a body of high scientific interest, both due to its similarity to the early-Earth and to the astrobiology community, the lakes present a unique mechanism for complex molecules in the upper atmosphere to access the incubatory environment of the interior. In-situ measurements following this process from beginning to end are achieved with the proposed mission architecture of Astraues, offering an opportunity to map this process like never before (Figure 1).

Figure 1. Astraeus aerial vehicle in operation in Titan's atmosphere.

2. Science Case

2.1. *Geomorphology*

Titan is a Solar System body with a dense atmosphere and where the stable existence of liquid on the surface has been proven. The only other body in the Solar System for which this is true is the Earth, and the similaries between these two seemingly distinct bodies do not end there.

Images taken from Voyager 1 in November 1980 allowed a deeper study of Saturn's moon Titan than had previously been possible from Earth, despite the haze and dense atmosphere, and later images of Titan taken over the 4-year nominal mission by the *Cassini* spacecraft covered approximately 90% of Titan's surface with spatial resolutions above 10 km [2] and much of it (∼40%) with higher resolution, from several kilometers down to around 1 km. The main optical characteristics of Titan's surface are bright and dark regions. Thus, it is found that light material is topographically high at lower latitudes, and dark material forms lower plains [3]. Due to the spectral difference and distribution of albedo, scientists were able to establish the heterogeneity of Titan's surface topography, as well as trace the extent of certain landforms and their boundaries.

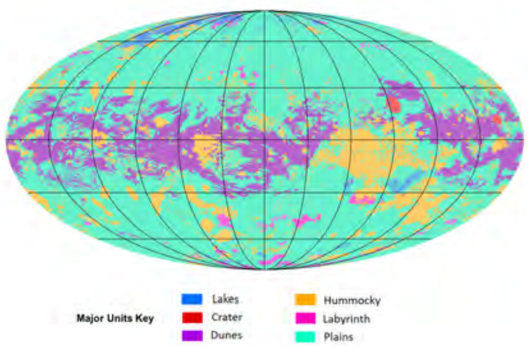

Figure 2. A global geologic map of Titan. Image credit: NASA/JPL-Caltech/ASU.

Informative, but incomplete observations in the infrared and radio wavelengths were taken by the *Cassini* spacecraft, provided by a synthetic aperture radar and a wide-angle and narrow-angle camera, observing in the visible and infrared. A lander segment, *Huygens*, obtained in-situ atmospheric data and near-surface remote sensing data in the visible and near-infrared with a suite of imagers [4], allowing the creation of a primary geological map consisting of structures (now numbering over 70), subsequently approved by the International Astronomical Union (IAU).

In 2019, a team of researchers from NASA's Jet Propulsion Laboratory and from the School of Earth and Space Exploration at Arizona State University presented the first geological map of Titan based on data from the *Cassini* spacecraft, which operated from 2004 to 2017 and made more than 120 overflights of Titan. This map can be seen in Figure 2.

This map, while allowing a presentation of Titan's geomorphology - showing extensive dune fields, plains, lakes and folding systems - requires further refinement. This general information on the appearance, together with the physical and chemical data obtained during the missions, already allows geologists to develop theories of Titan's evolution through time. However, the presence of more localised structures such as cryovolcanoes needs to be confirmed with conclusive evidence, meaning future explorers will require an appropriate mission profile and instrument resolution to capture them.

It is worth noting that cryovolcanism is not something unheard of in our Solar System. We know of at least 9 objects, including Titan, where cryovolcanic processes have either been recorded or there are convincing theories about their existence, these are: Earth, Mars, Enceladus (Saturn), Io (Jupiter), Europa (Jupiter), Titan (Saturn), Pluto, Triton (Neptune), Ceres [5].

The presence of signs of volcanism on Titan may confirm the theory of migration of methane and ethane from its interior by release of hydrocarbons into the atmosphere and subsequently deposition into lakes [6].

Evidence of activity

The equatorial and subequatorial zones are particularly dominated by dune fields, folded structures and even mountain systems (for example the Xanadu region), usually the result of tectonic activity [7]. Rolled rocks about 5 to 20 cm in size were visible at the landing site of the *Huygens* probe [8] and may be the product of erosive activity by flowing liquid in the past or present. Similar landscapes, caused by the activity of temporary or permanent streams can be observed on Earth and Mars [9]. However, surface fluids in the equatorial belt have not yet been detected, which means that weathering processes cannot be ruled out.

The structures of greatest interest are round-shaped, caldera-like[1] structures, around which traces of currents can be seen, interpreted by many scientists as cryovolcanoes, such as Ganesa Macula, Tortola Facula, or Winia Fluctus [10]. It is these structures which can shed light on the physical and chemical processes of Titan to help explain the nature of the hydrocarbons which have such a major influence on the appearance of the satellite, and are natural markers of the possible presence of biological molecules or other forms of life on its surface.

The extent of such structures extends for tens of thousands of kilometres and is probably less than a few hundred metres in height. The previous mostly global coverage of Titan provided by the Cassini mission lacked global sub-100 metre resolution imaging, meaning structures smaller than a few hundred meters remain a mystery.

Two highly visible crater-shaped structures have also been identified, Guabonito and Shikoku Fakula, located directly west of Xanadu, with no visible signs of a current, but presumably of impact or volcanic origin. It is worth noting that impact shapes on Titan are not widespread, although according to the existing data it is difficult to determine which structures (Menrva, Sinlap, Ksa for example) are of endogenous origin and which were formed by the influence of external factors.

The presence of such structures sometimes strongly resembles the 'Yamal craters', a central part of the Yamal Peninsula - the first cryovolcanoes detected on Earth. One of the main hypotheses of their formation is a methane explosion. Under the conditions of warming and gradual destruction of permafrost, methane is released and rises to the surface as a powerful explosive outburst of water and melted rocks.

Many structures interpreted on Titan as traces of flow or even as entire river systems may be areas that have undergone glacial activity in the past or present, with glaciers known to form entire valleys with diverse land-

[1] A caldera is a large cauldron-like hollow that forms shortly after the emptying of a magma chamber in a volcanic eruption.

forms. The formation of a glacier requires an underlying surface, constant negative temperature and atmospheric precipitation. Sometimes, though, solid precipitates can form at the surface due to a drop in temperature, as in the case of Pluto [11].

During its approach to Titan, *Cassini* observed the transition from fall to winter at the south pole and the onset of summer at the north pole. During the nominal mission, *Cassini* made 44 flyby of Titan over a four-year period from 2004 to 2008. Then, after the first extended mission was granted 27 more flybys took place, followed by another 56 flybys during the second extension. Due to the high atmospheric density, large diurnal temperature changes have not been recorded and are not expected on Titan. However, each of the four seasons on Titan lasts about seven Earth years, so seasonal changes will occur very slowly, meaning there is not yet a complete picture of atmospheric changes and, consequently, precipitation and temperature variability on Titan, meaning their possible effects cannot be estimated.

In order to shed light on Titan's geomorphology, and thus on its origin, development, external and internal processes, new investigations are needed, both by radar and optical instruments from orbit and by landing modules capable of analysing the atmosphere and surface at high resolutions and in-situ.

Some theories have described the theory of silicate magma at Titan, citing as evidence the presence of 40 Ar in Titan's atmosphere [12], a product of 4 °K decay. This suggests suggests magma degassing from the interior, where silicates are present, to the icy surface. However, with further in-situ measurements as described, it is impossible to confirm or disprove this theory.

2.2. *Atmosphere*

Titan is unique in the Solar System in that as a natural satellite of Saturn it sustains a substantial and dynamic nitrogen-methane atmosphere, and bodies of liquid on its surface [13, 14, 15]. Revealed in unprecedented detail by the Cassini-Huygens mission throughout the 2000s and 2010s, the thick, visibly opaque haze (Figure 5) is now known to support complex organic chemistry. Coupled with an internal ocean and viable pathways between the two, Titan's upper atmospheric and ionospheric photochemistry is of great importance in understanding the types of molecules which can be expected to be present within the Titan system (Figure 3).

A surprise discovery of the *Cassini* spacecraft was one made by the Cassini Plasma Spectrometer (CAPS), particularly by the electron spectrometer (ELS). This instrument was mounted on a single-plane rotating platform, designed to increase the field of view to which the instruments had access during a three-axis stabilised period of spacecraft motion, and would in-situ detect and analyse

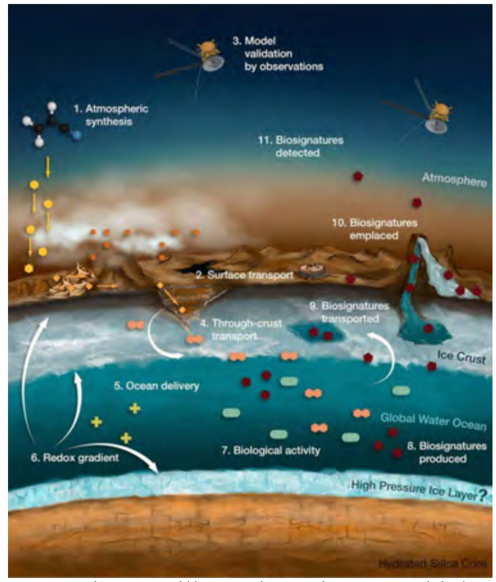

Figure 3. Diagram illustrating Titan's multiple atmospheric layers, surface and interior, showing a potential biosignature pathway. Credit: A. Karagiotas/T. Shalamberidze/NAI/JPL.

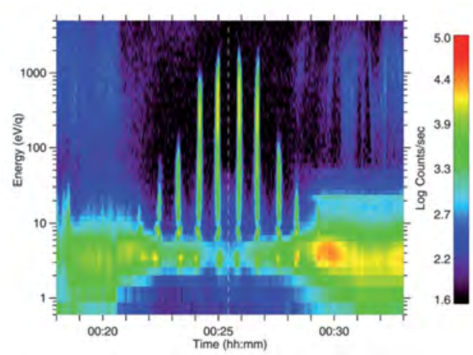

Figure 4. CAPS ELS spectrogram for 25 minutes around closest approach during one Titan encounter [16]. Note that shown is the magnitude of energy per particle.

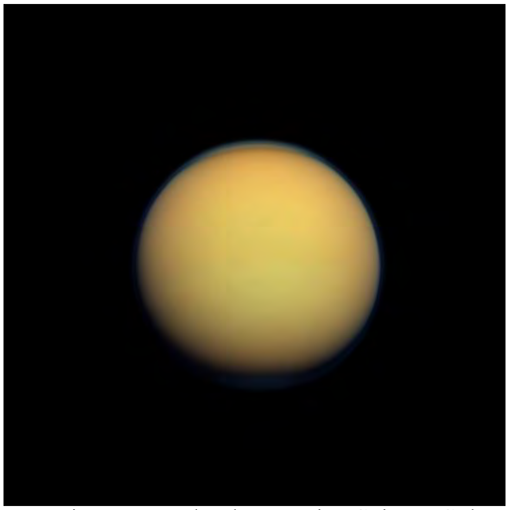

Figure 5. Titan as seen by the Imaging Science Subsystem onboard the *Cassini* spacecraft. Credit: NASA/JPL.

incident plasma particles. During the platform's oscillation between rotation limits, large spikes in incident energy were observed, as seen in Figure 4. These spikes, whose discussion has been presented in multiple papers [17, 18, 16], peak during the time the CAPS instrument was pointing in the direction of spacecraft travel, termed the ram direction, and are now known to show heavy negative ions in Titan's ionosphere. This means that the ion thermal velocity of these particles must have been much lower than the velocity of the spacecraft during its ionospheric passes, and by combining the ELS energy analysis with spacecraft velocity information, ion mass has been inferred.

Adapting Titan atmospheric models to account for these negative ions, their presence in the ionosphere can be understood, and their role in the fascinating and complex organic process on Titan is better known.

There are a number of key characteristics of these ions which have implications on a mission being designed to study them. Firstly, the lowest altitude at which they were observed is known to be $\sim 870\,\mathrm{km}$ [19] and as their rate of occurrence is seen to increase with decreasing altitude, a mission that can determine a more complete profile at lower altitudes is key. Another driver is a desire to understand the transport of these ions. A differential between dayside and nightside ion occurrence was observed, and an understanding of which side drives formation or disassociation is important to build more complete models of these ionospheric processes, and a better understanding of Titan's photochemistry in general. Latitudinal variation is also something that has been observed and needs to be better understood.

2.3. Lakes

Titan's prodomonantly nothern polar lakes present a potentially interesting interface between the active internal dynamics of Titan and the solar-driven chemistry of the upper-atmosphere. Given a lack of in-situ data from these lakes, they have only been observed from orbit by the *Cassini* spacecraft and so images with spatial resolutions larger than $100\,\mathrm{m}$ are all that is available. Sounding of the lakes using *Cassini's* Radar allowed for the weak determination of some lake bottoms and lake profiles. Similarly, observation of their dynamics and radar backscatter have allowed for some composition information to be inferred. While this produces results with rather wide error bars, it nevertheless allows for an estimation of lake properties and sizes. Particular open questions about Titan's lakes are [20]:

- Are Titan's lakes linked by subsurface reservoirs?
- Have Titan's lakes always been confined to the polar regions of the body?
- Were the dry basins of Titan's South Pole once lakes, similar to the North Pole?
- Are Titan's lakes truly methane dominated?
- What is the sink of Titan's photochemically produced ethane?
- What is the difference in composition between Titan's different lakes?

An understanding of compositional differences, already known at a high level, between Titan's lakes can be assumed to reveal clues about any subsurface reservoirs which may connect clusters of lakes. Measurement of lake compositions to high degrees of accuracy will enable the confirmation of interconnections. Furthermore, the question of ethane sinking in Titan's lakes would enable an understanding of the final phase of the journey of particles formed in Titan's upper atmosphere.

2.4. Surface Feature Targets

The Conex team has selected four strategic locations for the Astraeus mission, three of which are locations suitable for landing and detailed in-situ exploration. These are the lakes near Titan's north pole and the surrounding terrain. Additionally, another location of increased interest in the scientific community and in our team is a structure named Ganesa Macula, a theorised cryovolcanic structure [10]. During the Astraeus mission, we expect to fly at low speed at an altitude of about $40\,\mathrm{km}$ over the field of suspected cryovolcanic structures. In this way, the physical and chemical parameters of the atmosphere above the structure can be measured, and high spatial resolution imaging of the local topology can be performed.

When selecting locations for a detailed study, priority was given to surface lakes due to their aforementioned status as a mission science driver.

To date, there is no concrete consensus on the origin of the lakes in the northern polar region of Titan as with current data, it is impossible to firmly determine whether these hydrocarbon lakes are the result of the hydrological cycle and deposition of hydrocarbon precipitation, or the result of underground erosion of rocks, if such mechanisms exist. There are theories ranging from their origin as impact craters to those discussion the lakes' potential karst origin.

The round shape of some of the lakes has led scientists to speculate that they originated from the impact of another body into Titan's surface [21]. The raised rims and bright haloes surrounding some lakes, as well as their nested appearance, has led to the suggestion that some may be volcanic craters [22]. However, the concentration of lacustrine depressions in the polar region and their irregular shape make the theory of volcanic origin questionable. According to some researchers, the morphology and clustering of the lakes strongly resembles terrestrial karst lakes [21]. The fact that water ice is insoluble in methane or ethane leads us to believe that Titan's crust is not as simple as it first appears, but more data and research in this direction are needed.

Theoretically, the formation of lakes of this type could be preceded by hydrolaccoliths similar to those developed in the northern latitudes on Earth. They form in the permafrost zone and consist of frozen ground interbedded with ice. This process is also related to the drying up of the surface of thermokarst lakes.

Below are the characteristics of our selected locations, according to data from the Cassini mission:

Lake Kraken Mare This lake is the largest known lake on Titan (500 000 km^2) and is located at 68°N 310°W. It is located in a depression and reminiscent of terrestrial crater lakes. The diameter of the lake is 1170 km (>1100 km long). The main body of Kraken Mare is assumed to be at least 100 m deep and probably deeper than 300 m. It is thought to be filled with 70% methane, 16% nitrogen and 14% ethane [23]. Shallow capillary waves 1.5 cm high moving at 0.7 m/s have been detected on the surface of Kraken Mare.

Lake Ligeia Mare This is the second largest liquid body on the surface of Titan, after Kraken Mare, and is located at 79°N 248°W. Measuring roughly 420 km (260 mi) by 350 km (217 mi) across, it has a surface area of about 126 000 km^2, and a shoreline over 2000 km (1240 mi) in length. It is mostly composed of liquid methane, with unknown but lesser components of dissolved nitrogen and ethane. The lake may be hydrologically connected to the larger Kraken Mare and may be studied in association with Kraken Mare. The average depth is on the order of about 50 m, while the maximum depth is probably greater than 200 m. The total volume is likely to be greater than 7000 km^3 [23].

Lake Mackay Lacus Located east of the previous two lakes at 78.32°N 97.53°W, it is not particularly large being only 180 km in diameter. However, its relative proximity to our other science targets make it an important feature when considering that it is hoped multiple lakes can be investigated.

Ganesa Macula Ganesa Macula has a diameter of 180 km, and the coordinates of the center are W 49.7°N. 87.3° W. In the center is a 20-kilometer bright region of unknown origin. Within Ganesa Macula, the East, West and Central calderas are distinguished. The West Caldera and the irregularly shaped crater stream can be seen about 1070 km from the western edge of Ganesa. The caldera is about 18 km in diameter, the flow is at least 84 km long, and the minimum area is 1020 km^2. The largest field complex of the flow (Winia Fluctus, at least 23 700 km^2) is located about 1340 km east of the eastern edge of Ganesa. The flow extends from 50° west longitude, 52° north latitude to 44° west longitude, 47° north latitude [10].

Interpreting SAR data from the Cassini mission, scientists suggest that Ganesa has fairly steep slopes and a flat top, similar to the pancake domes on Venus imaged by Magellan spacecraft [24, 25]. When considering Titan's cryovolcanoes [22], scientists conducted a detailed study of possible cryovolcanic flows, based on radar data and modelling. According to the data obtained, the flows are directionally divided and reach a length of at least 80 km, covering an area of at least 800 km^2. Thus, these structures are comparable to volcanic flows on Mars [26] and Venus [27]. Consequently, a theory has been developed that Ganesa Macula is a shield volcano similar to those common on Earth, Venus, Mars and the Moon. It is worth noting that the structures described strongly resemble glacial valleys, which does not, however, rule out the existence of cryovolcanic structures that have been subject to glacial erosion over time.

2.5. Science Closure

It is clear that, as is always the case with planetary science targets, Titan presents many distinct regions of interest. The challenge, therefore, presented to the engineering team is to deliver access to these multiple regions of interest and if possible minitor the pathway from particle formation in Titan's upper atmosphere down to the surface of the moon. The key driving requirements can therefore be summaried as:

- Trace the spatial and chemical pathway of particles from their formation in the photochemically active upper atmosphere to the surface of Titan.
- Determine the longevity of particles on Titan's surface (if they indeed complete a journey to the surface) and understand their behaviour once they arrive.
- Identify any subsurface linking of surface liquid features on Titan.
- Understand the nature of surface liquid features on Titan.
- Understand past and ongoing activity at Titan, including the role of cryovolcanos in the moon's internal-external interface.

3. Mission Concept

The Astraeus Mission Architecture must consist of orbital and lander segments to meet the science objectives identified in Section 2. The trade off between different configurations for each segment as well as the major interfaces between and within the segments are considered in the following sections. The result of this is a Main Orbital Spacecraft (MOS) which comprises the major bus element that will hold all other spacecraft. The MOS is also be home to 2U CubeSats, called the Mites, that will be deployed from 1400 km in altitude into a low decay-rate orbit to categorise the upper atmosphere of Titan and how it changes with each season.

The lander segments will be housed in an entry module attached to the MOS. The major lander segments are an air vehicle (Mayfly) with a cable-deployed subsea vehicle (Manta). An ability to perform in-situ measurements within Titan's seas and lakes is the primary objective of this mission, but these bodies of hydrocarbons span approximately 68-85° North. Geomophological features such as the connection between lakes and seas require aerial and subsea exploration. Therefore, the air and subsea vehicle (ASV) are operationally depenendent upon one another, being connected by a permenant mechanical link between the two vehicles supporting a data and power cable.

The ASV will enter the atmosphere using a heritage Entry Module design with additional requirements for long duration descent and high-altitude flights over Ganesa Macula. This enables validation of the northernmost evidence of cryovolcanism on Titan during descent without extending the nominal exploration range of the ASV.

3.1. MOS

The MOS is the hub of the Astraeus mission with the purpose of transferring and supporting the lander segments to Titan as well as hosting the high-altitude anion experiment carried by the Mites. The MOS has also been designed to collect magnetometer data and operate a synthetic aperture radat with an average resolution of 100 m. It features a 4 m-diameter deployable hgh gain antenna for communications between Astraeus and Earth during transit to Titan. The MOS will function as a relay between Earth and Titan during nominal operations but in addition, the lander segments will be able to communicate directly with Earth. This ensures there is no reliance upon the MOS for primary communications once all Mites have been deployed.

The orbit and configration of the MOS were driven by the high-altitude atmospheric experiements required on Titan. NASA's *Cassini* spacecraft identified the presence of heavy anions between 900 km and 1400 km during flybys with the CAPS instrument. Astraeus can expand this body of data over a greater range of longitudes and latitudes with an eccentric polar or near-polar orbit around Titan. This data must also be conducted continuously so that a similar profile of annual data as produced by *Cassini* could be collected by Astraeus. These constraints lead to two major configurations for the orbital segment: Single-ship or Mothership.

A top-level requirement of the MOS is to minimise the mass and power of the spacecraft. Minimising payload mass and combining systems is an ideal way to do this. For example, there are packaging constraints for the Astraeus Mission if emergent heavy launch systems such as Vuclan Centaur, Ariane 64 or New Glenn were to be used. This will likely require mechanisms to deploy the vehicle from a stowed configuration to an operational configuration. We propose the magnetometer be mounted onto the end of a deployable SAR array in a similar way to the solar array on NASA's Juno spacecraft.

The subsystem CBE mass percentages were selected using conservative mass budget numbers from the SMAD. The total mass of the MOS was derived based on the mass of the desired payloads. The growth MGA factors applied to the CBE masses are derived from the AIAA standards. The current payload list is subject to change based on the priority of the science goals. The aim in the next phase will be to refine the CBE mass percentages through detailed analysis of the subsystems.

An additional constraint on the subsystem mass will be the fuel mass required for establishing the nominal orbit and station keeping. The fuel requirement will drive the mass of the propulsion and attitude control system. The resulting cascade in refined CBE masses will reduce the MGA factors and subsequently improve the accuracy of the MOS's predicted mass. This is all subject to the chosen trajectory which is currently being investigated. However, the predicted mass will trend downwards once this trajectory has been optimised.

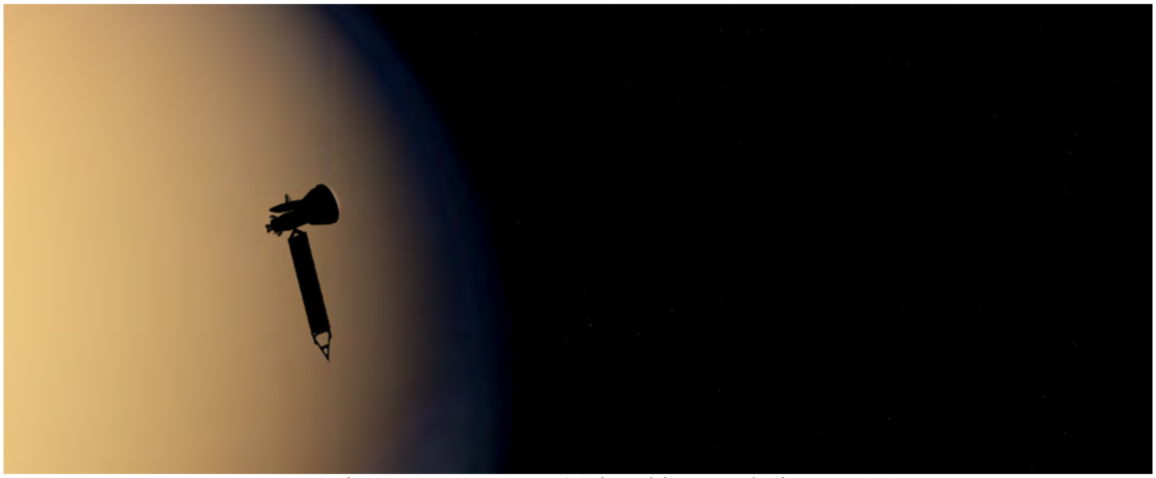
Figure 6. Astraeus MOS in orbit around Titan.

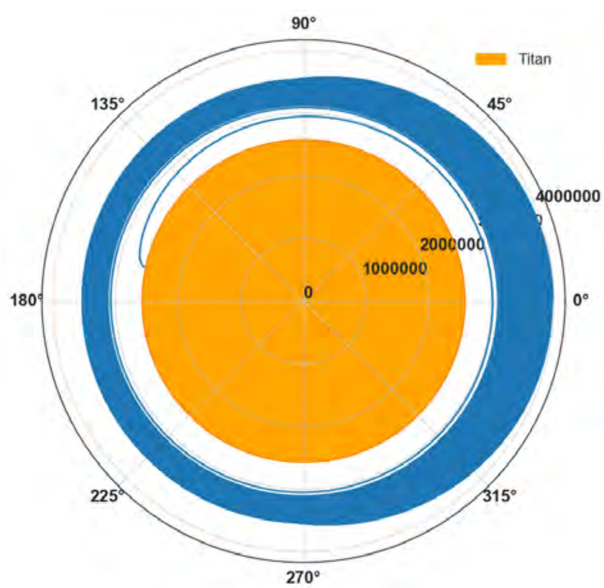

Figure 7. Modelling of the descent of Arcanum Mites.

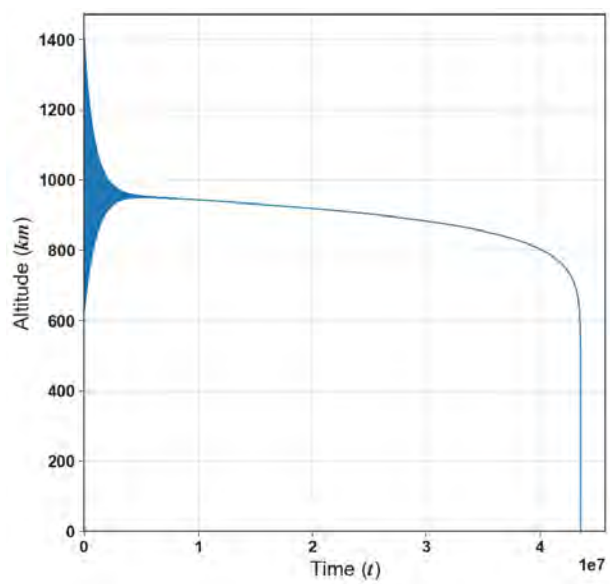

Figure 8. Altitude against time plot for the Arcanum Mites during atmospheric decay.

3.2. Mites

The Mites are 2U CubeSats based on the QB-50 Project which used a constellation of CubeSats in LEO to conduct in-situ particle detection using an ion-neutral mass spectrometer (INMS). The Mites will be released from the MOS approximately once every Earth year into a low decay rate orbit from 1400 km in altitude as shown in Figures 7 and 8. The major difference in the design of the Mites and QB-50 is the electrical and power subsystem. The Mites would only be able to generate between 0.02–0.04 W using solar panels. The PocketRTG concept as a slightly greater power output but is constantly generating power compared to the solar power solution. This can be used to charge a battery and pulse between the INMS experiment and communication.

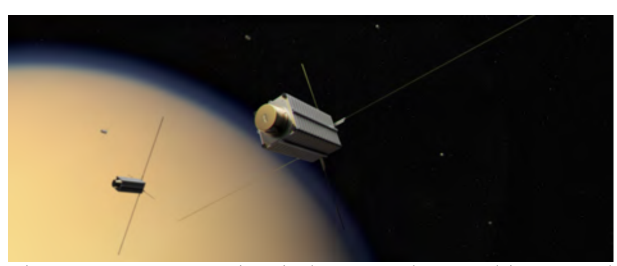
Figure 9. Astraeus Mites in low-rate decay orbits around Titan.

Figure 10. Astraeus Mayfly in flight around Titan.

3.3. *Mayfly*

Mayfly is a hybrid flying-wing UAV with fixed motors for vertical and horizontal flight. This configuration is an evolution of NASA's Dragonfly spacecraft to enable high endurance flights which make use of mixed flight modes. This includes VTOL, transition into horizontal flight, powered horizontal flight and horizontal glides. Titan's denser atmosphere and lower gravitational acceleration compared to Earth benefit the flying-wing configuration. It enables high-altitude glides and low-power horizontal flights where the roll, pitch and yaw control can be improved by mixing aileron and elevon input with rotor inputs.

3.4. *Manta*

The Sea Vehicle, Manta, is a deployable probe from the Air Vehicle, Mayfly. This probe features buoyancy tanks and electric pump-jet propulsion to translate its motion in all directions. The CONOPS for the lander segment requires Mayfly to complete aerial surveillance of potential landing sites on the lakes of Titan. The system lands on the surface and deploys Manta into the lake. The mechanical connection between the two systems was chosen to be a cable. A spooled cable provides data and power transmission to the Manta reducing the mass of these systems onboard the sea vehicle significantly. This greatly reduces the total mass and power consumption. This cable does provide increased hydrodynamic drag characteristics once fully deployed. This results in a buoyancy requirement for Mayfly which, helpfully, does not compromise the design of the air vehicle in favour of the sea vehicle. The conceptual hydrodynamics of the Manta are aided by a rounded front and ideal teardrop shape as shown in Figure 9. The two frontal hydrofoil sections aid in control of the sea vehicle to provide constant downforce during forward motion. This reduces the reliance upon the buoyancy tanks and thus reduces the power required by pumps. The attitude control is provided by small pump jets for a low power and low velocity change in orientation when Manta undertakes sub-sea exploration.

3.5. *Entry Module*

The Entry Module (EM) must encapsulate the mated air and sea vehicles (ASV) from launch to atmospheric entry at Titan, protecting them from the conditions of free space and the aerothermodynamic loads experienced when decelerating through Titan's thick atmosphere. It must also facilitate the safe deployment of the ASV. Two main design concerns constrain the parameters of the entry module; the structure of the spacecraft within, and the parameters of the descent trajectory. The former influences the peak deceleration and vibration the descent vehicle can tolerate, as well as informing the overall geometry of the encapsulating module (which in turn influences heat flow behaviours around the vehicle, amongst other things). The latter determines the peak heat flux, peak dynamic pressure, and heat load.

At this stage the specifics of the Titan orbit are undefined. However, an estimate of mass based on entry corridor characteristics in heritage missions can be derived. These missions consist mainly of those sent to Mars, and also the Cassini-Huygens mission [28], the best analogue available due to also being a Titan surface probe. We also take inspiration from the proposed NASA Dragonfly mission [29], as well as the AVIATR Titan aeroplane mission concept [30].

The aforementioned Titan missions differ from Astraeus in that they all pursue direct descent trajectories when encountering Titan. In this case, however, the EM is deployed from an elliptic near-polar orbit of Titan, meaning the deceleration necessary, and consequently the heat load, will be lower. Therefore, though they are still useful, the past and proposed Titan missions are not perfect analogues. For such mission-critical hardware like the aeroshell, the emphasis is placed on reliability of materials and structures used, for which the experience of heritage missions is invaluable. All material dimensions are subject to revision.

The TPS consists of the backshell and the forebody, or heat shield, both of which consist of a structural body, an insulating layer and an ablative external layer. Additional systems include parachutes and parachute pyro assemblies, orientation control systems, batteries, electronics and sensors. The supporting structure of the backshell consists of a monocoque isogrid of roll-formed Aluminium 10 mm thick, formed into the frustum of a right circular cone of 60 degree half-angle. This angle is maximised to increase drag, but constrained by shock wave detachment; after shock wave detachment, an entry vehicle must carry significantly more shocklayer gas around the leading edge stagnation point. Consequently, the aerodynamic centre moves upstream thus causing aerodynamic instability. For nitrogen atmospheres the limiting angle is about 60 degrees. The ablative layer consists of 10 mm Lockheed Martin SLA-561V lightweight abla-

Figure 11. Astraeus Manta diving in Titan's surface lakes.

tor, used in all NASA Mars landers and rovers since the Viking programme. As the heat flux over the backshell is expected to be significantly lower than that over the forebody, this layer need not be very thick; significant ablation would be expected if heat flux reaches around $100\,\mathrm{W/m^2}$, which at this stage would be well clear of predicted loads.

In primarily nitrogen atmospheres, radiative heating accounts for a much larger portion of the total thermal load than for other atmospheres explored. This is due to the formation of highly radiative cyanogen groups in the bow shock, where methane dissociates and reacts with nitrogen [31]. To protect the ASV a matrix of multi-layer insulation (MLI) is bonded to the inner surface of the backshell and forebody. Prior to more detailed thermal analysis, we set 100 W as the maximum acceptable power radiated into the ASV cavity (the same threshold as for *Huygens*), requiring 10 layers totalling approximately 100 μm [32]. The MLI also doubles as radiation protection during the cruise phase of the mission. The structure of the forebody is a carbon-fibre-reinforced plastic honeycomb shell akin to that used on the *Huygens* EM. To this is bonded the 3.7 m diameter ablative heat shield, which consists of a phenolic resin felt reinforced with silica fibres, of the same kind proved in the *Huygens* heat shield [33]. This provides a tolerance of $140\,\mathrm{W/m^2}$. The back-cap on the EM will be formed from silicone-impregnated reusable ceramic ablator (SIRCA), used in the backshell interface plates of the Mars Science Laboratory and Mars 2020 missions. It is chosen due to its ease of manufacture and forming into complex shapes. It will accommodate mounting fixtures to connect to the orbital module and house the parachute deployment apparatus. It has a heritage heat flux tolerance of $200\,\mathrm{W/m^2}$, well in excess of what we expect it will be exposed to during this mission.

Two parachutes will be carried, the first a hypersonic drogue chute used to deploy the larger main chute, which will then carry the EM the majority of the way to deployment of the payload. Both parachutes are of the disc-gap-band variety, used in all NASA Mars missions, as well as by *Huygens* and many other spacecraft. The specifics of the parachutes will depend on the required deceleration of the descent flight path.

Using the working masses of the air and sea vehicles we obtain a structural mass prediction of approximately 300 kg. Initial estimates for other subsystems masses require further analysis to constrain to more precise values in future.

3.6. *Future Developments*

Some essential questions regarding the three components to answer moving forward include:

MOS What is the power budget needed for the MOS throughout its service life? The MOS has a design life of at least 7 years to host the INMS CubeSats for at least two seasons on Titan. This design life, coupled with the low solar intensity at the Saturn planetary system, necessitates an RTG power source. However, there is a greater consideration that must be given to the type of RTG selected as this will have a knock-on effect on the mass, power and data-link budgets of the MOS. The CBE Mass for the electrical and power subsystem would facilitate several combinations of RTG systems. A further analysis of the power budget would determine whether a static RTG would be applicable for nominal MOS operations. If not, then a configurable DRPS would allow for a power system that operates with a smaller margin to the power budget. Thus, the mass of each subsystem can reduce the total mass.

Mites What is the power budget needed for the Mites' descent into Titan's atmoshpere? A detailed power budget will need to be completed to further validate the current PocketRTG concept. This will identify if there are a sufficient number of duty cycles per Earth year to complete the experiment over a range of altitudes, latitudes and longitudes. This is why we currently carry 20 Mites on board the MOS and further analysis could reduce this number. However, it may be prudent to keep the 20 Mites to account for deployment failures due to long-duration storage. The PocketRTG concept could be further developed using emergent DRPS technologies like the Stirling engine collectors on the opposite side of the CubeSat. This would extend the craft from a 2.5U to 3U spacecraft with a comparable increase in efficiency. This requires a detailed analysis with specific experts in RTG and RPS design to validate the concept as being reasonable for the Mites.

Entry Module How tight is the entry corridor in order to ensure the spacecraft touches down within the target area? The principles of conservative design dictate that from this can be derived two soft worst cases to use to inform the choice of material thickness for the aeroshell, with an undershoot and an overshoot trajectory constraining the boundaries of the flight path (there are also the corresponding hard worst cases, being the undershoot trajectory with the shallowest entry angle before skipping off the atmosphere, and the overshoot trajectory being the steepest approach the vehicle can tolerate, setting the upper bound for heat load).

How strong are the winds that can be expected on descent? The presence of strong winds may be cause for concern, especially when parachutes are deployed, if they should be strong enough to blow the vehicle far away from its desired landing site, or from a wet landing to a hard landing if the vehicle is not designed to land on solid ground.

Manta What is the maximum exploration depth required of Manta? This affects the main cable design which in turn will tell us more about the hydrodynamic drag envelope. There are a series of positive knock-on effects if the maximum exploration depth can be selected. The overall benefit is that the CBE mass percentages of the total subsystem improves significantly. This improved the design of Mayfly as Manta can be considered as a system with a significantly lower variance in its final mass. Thus, the flight envelope for Mayfly is less broad.

4. Astrodynamics

The trajectory analsysis to distant planets requires multiple considerations like fuel quantity, burn time, and transfer time. Multiple gravity assist maneuvers have to considered in order to reach saturn as the delta v has to be kept within low to allow for a good amount of payload. The preliminary trajectory analysis done shows that the trajectory from earth (GTO) to saturn (rp = 350,000 km and e = 0.548) can be achieved with a delta v of around 5.8 km/s using gravity assists from Venus, Earth and Jupiter. This would take around 10 years. A more detailed trajectory analysis will be developed as the mission concept matures.

The seasons of Titan vary within 7-year periods in relation to the Saturnian 29.5 Earth-year orbit. As Astraeus aims to launch after 2050 and is estimated that it will arrive 10 years later, the seasons that would be observed in the northern hemisphere would be transitioning from winter into spring by 2065 and Spring into Summer by 2072. *Cassini* witnessed an ever-evolving picture of what the effect of autumn and winter in the northern hemisphere contributed to between its first encounter in 2004 and it's final in 2017. This would allow for observations to continue through the cycle from where *Cassini* finished. Where *Cassini* had a brief observation period of all of the seasons for both hemispheres, Astraeus can have a more in-depth investigation towards the warmer seasons in the northern hemisphere [34, 35].

Due to the variations from transitioning between the summer and winter equinoxes being over 14 Earth-year period, a greater understanding of the seasonal variations in both the atmosphere and on the surface can be studied. Cassini data has already been analysed on the difference in the temperature, gas, and aerosol distributions throughout the layers of Titan's thick atmosphere over the polar and equatorial regions [36, 37]. With this proposed mission, there can be a greater focus on surface changes through the warmer period with insitu monitoring over a period of months at the very least in comparison to the 72 minutes of Huygens. Other aspects that can be observed include unanswered questions from Cassini and a better understanding of the hydrocarbon haze changes, formation of clouds, different climates and potentially a deeper look into the anti-greenhouse effect resulting from different altitudes of haze.

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References

[1] James McKevitt. "Optimisation of a Hydrodynamic SPH-FEM Model for a Bioinspired Aerial-aquatic Spacecraft on Titan". In: *Global Space Exploration Conference 2021*. International Astronautical Federation, 2021.

[2] E. P. Turtle et al. "Cassini imaging of Titan's high-latitude lakes, clouds, and south-polar surface changes". eng. In: *Geophysical research letters* 36.2 (2009), L02204–n/a. ISSN: 0094-8276.

[3] Laurence A. Soderblom et al. "Correlations between Cassini VIMS spectra and RADAR SAR images: Implications for Titan's surface composition and the character of the Huygens Probe Landing Site". eng. In: *Planetary and space science* 55.13 (2007), pp. 2025–2036. ISSN: 0032-0633.

[4] Caitlin A Griffith et al. "CHARACTERIZATION OF CLOUDS IN TITAN'S TROPICAL ATMOSPHERE". eng. In: *The Astrophysical journal* 702.2 (2009). ISSN: 1538-4357.

[5] Sarah A. Fagents et al. "5 - Cryovolcanism". eng. In: *Planetary Volcanism across the Solar System*. Elsevier Inc, 2022, pp. 161–234. ISBN: 0128139889.

[6] Sushil K. Atreya et al. "Titan's methane cycle". eng. In: *Planetary and space science* 54.12 (2006), pp. 1177–1187. ISSN: 0032-0633.

[7] R. D. Lorenz et al. "The sand seas of titan: Cassini RADAR observations of longitudinal dunes". In: *Science* 312.5774 (May 2006), pp. 724–727. ISSN: 00368075. DOI: 10.1126/science.1123257.

[8] H.U. Keller et al. "The properties of Titan's surface at the Huygens landing site from DISR observations". eng. In: *Planetary and space science* 56.5 (2008), pp. 728–752. ISSN: 0032-0633.

[9] Antonio J Paris and Laurence A Tognetti. "Ancient River Morphological Features on Mars versus Arizona's Moenkopi Plateau". eng. In: *Journal of the Washington Academy of Sciences* 106.1 (2020), pp. 59–76. ISSN: 0043-0439.

[10] "Release of volatiles from a possible cryovolcano from near-infrared imaging of Titan". eng. In: *Nature* 435.7043 (2005), pp. 786–789. ISSN: 0028-0836.

[11] Tanguy Bertrand et al. "Equatorial mountains on Pluto are covered by methane frosts resulting from a unique atmospheric process". eng. In: *Nature communications* 11.1 (2020), pp. 5056–5056. ISSN: 2041-1723.

[12] H. B NIEMANN et al. "The abundances of constituents of Titan's atmosphere from the GCMS instrument on the Huygens probe : Huygens probe on titan". eng. In: *Nature (London)* 438.7069 (2005), pp. 779–784. ISSN: 0028-0836.

[13] V. Vuitton et al. "Chemistry of Titan's atmosphere". In: *Titan: Interior, surface, atmosphere, and space environment*. Ed. by I. Mueller-Wodarg et al. First. Cambridge: Cambridge University Press, 2014.

[14] B Bezard, R. V. Yelle, and C. A. Nixon. "The general circulation of Titan's lower and middle atmosphere". In: *Titan: Interior, surface, atmosphere, and space environment*. Ed. by I Mueller-Wodarg et al. First. Cambridge: Cambridge University Press, 2014.

[15] M. Mastrogiuseppe et al. "Deep and methane-rich lakes on Titan". In: *Nature Astronomy* 3.6 (June 2019), pp. 535–542. ISSN: 23973366. DOI: 10.1038/s41550-019-0714-2.

[16] Andrew J. Coates et al. "Negative ions at Titan and Enceladus: recent results". In: *Faraday Discussions* 147.0 (Nov. 2010), pp. 293–305. ISSN: 1364-5498. DOI: 10.1039/C004700G.

[17] A. J. Coates et al. "Discovery of heavy negative ions in Titan's ionosphere". In: *Geophysical Research Letters* 34.22 (Nov. 2007). ISSN: 1944-8007. DOI: 10.1029/2007GL030978.

[18] A. J. Coates et al. "Heavy negative ions in Titan's ionosphere: Altitude and latitude dependence". In: *Planetary and Space Science* 57.14-15 (Dec. 2009), pp. 1866–1871. ISSN: 0032-0633. DOI: 10.1016/J.PSS.2009.05.009.

[19] K. Ågren et al. "Detection of currents and associated electric fields in Titan's ionosphere from Cassini data". In: *Journal of Geophysical Research: Space Physics* 116.A4 (Apr. 2011), p. 4313. ISSN: 2156-2202. DOI: 10.1029/2010JA016100.

[20] C.A. Nixon et al. "Titan's cold case files - Outstanding questions after Cassini-Huygens". In: *Planetary and Space Science* 155 (June 2018), pp. 50–72. ISSN: 0032-0633. DOI: 10.1016/J.PSS.2018.02.009.

[21] Jonathan L Mitchell. "Coupling Convectively Driven Atmospheric Circulation to Surface Rotation: Evidence for Active Methane Weather in the Observed Spin Rate Drift of Titan". eng. In: *The Astrophysical journal* 692.1 (2009), pp. 168–173. ISSN: 0004-637X.

[22] R.M.C. Lopes et al. "Cryovolcanic features on Titan's surface as revealed by the Cassini Titan Radar Mapper". eng. In: *Icarus (New York, N.Y. 1962)* 186.2 (2007), pp. 395–412. ISSN: 0019-1035.

[23] E. R. Stofan et al. "The lakes of Titan". In: *Nature* 445.7123 (Jan. 2007), pp. 61–64. ISSN: 14764687. DOI: 10.1038/nature05438.

[24] Betina Pavri et al. "Steep-sided domes on Venus: Characteristics, geologic setting, and eruption conditions from Magellan data". eng. In: *Journal of Geophysical Research* 97.E8 (1992), pp. 13445–13478. ISSN: 0148-0227.

[25] LS Crumpler. "Geotraverse from Xanthe Terra to Chryse Planitia: Viking 1 Lander region, Mars". eng. In: *Journal of geophysical research. Planets* 102.E2 (1997), pp. 4201–4218. ISSN: 2169-9097.

[26] Rosaly M. C. Lopes and Christopher R. J. Kilburn. "Emplacement of lava flow fields: Application of terrestrial studies to Alba Patera, Mars". eng. In: *JOURNAL OF GEOPHYSICAL RESEARCH-SOLID EARTH AND PLANETS* 95.B9 (1990), pp. 14383–14397. ISSN: 0148-0227.

[27] Kari P. Magee and James W. Head. "Large flow fields on Venus: Implications for plumes, rift associations, and resurfacing". eng. In: *Special papers (Geological Society of America)* 352 (2001), pp. 81–101. ISSN: 0072-1077.

[28] K.C. CLAUSEN et al. "THE HUYGENS PROBE SYSTEM DESIGN". In: *Space Science Reviews* (2002), pp. 155–189.

[29] Christopher Scott et al. "Preliminary Interplanetary Mission Design and Navigation for the Dragonfly New Frontiers Mission Concept". In: Aug. 2018.

[30] J. W. Barnes et al. "AVIATR—Aerial Vehicle for In-situ and Airborne Titan Reconnaissance". In: (2011).

[31] H. Porat, R. G. Morgan, and T. J McIntyre. "STUDY OF RADIATIVE HEAT TRANSFER IN TITAN ATMOSPHERIC ENTRY". In: 2012.

[32] K. Daryabeigi. "Thermal Analysis and Design of Multi-layer Insulation for Re-entry Aerodynamic Heating". In: 2001.

[33] J. M. Bouilly. "THERMAL PROTECTION OF THE HUYGENS PROBE DURING TITAN ENTRY: LAST QUESTIONS". In: ().

[34] N. A. Teanby et al. "Seasonal Evolution of Titan's Stratosphere During the Cassini Mission". eng. In: *Geophysical research letters* 46.6 (2019), pp. 3079–3089. ISSN: 0094-8276.

[35] Sandrine Vinatier et al. "Seasonal variations in Titan's middle atmosphere during the northern spring derived from Cassini/CIRS observations". eng. In: *Icarus (New York, N.Y. 1962)* 250 (2015), pp. 95–115. ISSN: 0019-1035.

[36] A. Coustenis et al. "Titan's neutral atmosphere seasonal variations up to the end of the Cassini mission". eng. In: *Icarus (New York, N.Y. 1962)* 344.1 (2020), pp. 113413–. ISSN: 0019-1035.

[37] S. M. Horst. "Titan's atmosphere and climate". eng. In: *Journal of geophysical research. Planets* 122.3 (2017), pp. 432–482. ISSN: 2169-9097.