Cyclopropenylidene.

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Introduction:

Cyclopropenylidene(c-C_3H_2) is a carbene which is partially aromatic molecule, it was recently found in 'Titan' saturns largest moon which is actually bigger than mars and showed similarities to Earth in its atmosphere. This moon has oceans, rivers and seas just like Earth but instead of water they are of Methane and Ethane. But they found a weird molecule called Cyclopropenylidene which was not found on earth but were only seen in laboratories due to its highly reactivity. Carbene is produced from nitrogen containing compound known as diazo compound. Since Titan has nitrogen, benzene, hydrogen, carbon, methane, ethane etc besides that I think there might be a metal 'Rhodium' which will be an important element for generation of DNA in Titan. Diazometane reacts with olefins to produce cyclopropanes

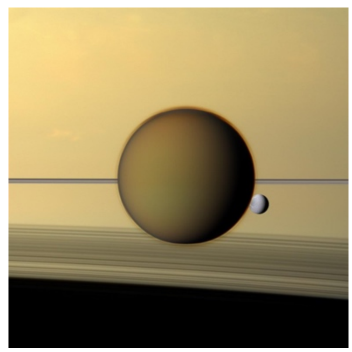
1,3- di polar cycloaddition forms pyrazoline which undergoes denitrogenation under photochemical or thermal decomposition to produce cyclopropane by releasing N2 as byproduct . The diazocompound reacts with metal catalysis i.e Rhodium. Methyl phenyldiazoacetate and other diazo derivatives are precursors to donor acceptor carbenes which can be used for cyclopropanation. These reactions are catalyzed by dirhodium tetraacetate or related chiral derivatives.

A novel DNA-based hybrid catalyst comprised of salmon testes DNA and an iron(III) complex of a cationic meso-tetrakis(N-alkylpyridyl)porphyrin was developed. When the N-methyl substituents were placed at the orthoposition with respect to the porphyrin ring, high reactivity in catalytic carbene-transfer reactions was observed under mild conditions, as demonstrated in the catalytic enantioselective cyclopropanation of styrene (benzene) derivatives with ethyl diazoacetate (EDA) as the carbene precursor. A remarkable feature of this catalytic system is the large DNA-induced rate acceleration observed in this reaction and the related dimerization of EDA.

Iron porphyrin have been employed successfully in carbene transfer reaction even in aqueous media. Elegant recent studies with engineered p450 and in combination with living cells have demonstrated that these reactions are biocompatible and enantioselective cyclopropanation has been reported albeit mostly under strictly anaerobic condition

I think the colour of Titan is yellow because of yellow gas produced by diazomethane and though benzene is colourless the aged sample of benzene is yellowish .

Since I'm a dentist student, carbene is very useful in pharmaceutical and for that clinical research on cyclopropenylidene is must even study on methanogenic archaea which causes dental plaque, oral disease, colon disease, vaginal disease even gut disease is important for further life in Titan.



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Saturn's fourth-largest moon, Dione, can be seen through the haze of the planet's largest moon, Titan, in this view of the two posing before the planet and its rings from NASA's Cassini spacecraft.

Acknowledgments: For additional reference you can go through this link https://solarsystem.nasa.gov/moons/saturn-moons/titan/overview/

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MISSION GOALS AND OBJECTIVES: WHAT SCIENCE IS DRAGONFLY GOING TO DO? Jason W. Barnes[1], Elizabeth P. Turtle[2], Melissa G. Trainer[3], Ralph D. Lorenz[2], Shannon M. MacKenzie[2], William B. Brinckerhoff[3], Morgan L. Cable[4], Carolyn M. Ernst[2], Caroline Freissinet[5], Kevin P. Hand[4], Alexander G. Hayes[6], Sarah M. Hörst[7], Jeffrey R. Johnson[2], Erich Karkoschka[8], David J. Lawrence[2], Alice Le Gall[9, 10], Juan M. Lora[11], Christopher P. McKay[12], Richard S. Miller[2], Scott L. Murchie[2], Catherine D. Neish[13, 14], Claire E. Newman[15], Jorge Núñez[2], Mark P. Panning[4], Ann M. Parsons[3], Patrick N. Peplowski[2], Lynnae C. Quick[3], Jani Radebaugh[16], Scot C. R. Rafkin[17], Hiroaki Shiraishi[18], Jason M. Soderblom[19], Kristin S. Sotzen[2], Angela M. Stickle[2], Ellen R. Stofan[20], Cyril Szopa[5], Tetsuya Tokano[21], Thomas Wagner[22], Colin Wilson[23], R. Aileen Yingst[13], Kris Zacny[24], and Simon C. Stähler[25] [1]University of Idaho; Department of Physics; Moscow, Idaho 83844-0903, USA [2]Applied Physics Laboratory; Johns Hopkins University; Space Exploration Sector; Laurel, Maryland 20723, USA [3]NASA Goddard Spaceflight Center; Mail Code: 690; Greenbelt, Maryland 20771, USA [4]NASA Jet Propulsion Laboratory; California Institute of Technology; Pasadena, California 91126, USA [5]LATMOS/IPSL, CNRS; Guyancourt, 78280, FRANCE [6]Cornell University; Department of Astronomy; Ithaca, New York 14853, USA [7]The Johns Hopkins University; Department of Earth and Planetary Sciences; Baltimore, Maryland 21218, USA [8]Lunar and Planetary Laboratory; University of Arizona; Tucson, Arizona 84721, USA [9]LATMOS/IPSL; UVSQ Université Paris-Saclay, Sorbonne Université; CNRS, FRANCE [10]Institut Universitaire de France (IUF); Paris, FRANCE [11]Yale University; Department of Earth and Planetary Sciences; New Haven, Connecticut 06511, USA [12]NASA Ames Research Center; Space Science Division; Moffett Field, California, USA [13]Planetary Science Institute; Tucson, Arizona 85719, USA [14]The University of Western Ontario; Department of Earth Sciences; London, Ontario, N6A 3K7 Canada [15]Aeolis Research; Pasadena, California, 91101 USA [16]Brigham Young University; Department of Geological Sciences; Provo, Utah 84602, USA [17]Southwest Research Institute; Boulder, Colorado 80503, USA [18]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency; Sagamihara, 252-5210, Japan [19]Massachusetts Institute of Technology; Department of Earth and Planetary Sciences; Cambridge, Massachusetts 02139, USA [20]National Air and Space Museum; Washington, DC 20560, USA [21]Universität zu Köln; Institut für Geophysik und Meteorologie; Köln 50923, GERMANY [22]NASA Headquarters; Washington, DC 20546, USA [23]Oxford University; Atmospheric, Oceanic and Planetary Physics; Oxford, OX1 3PU, UNITED KINGDOM [24]Honeybee Robotics; Pasadena, California 91103, USA [25]Institute of Geophysics; ETH Zürich; Zürich

Introduction: While in principle a Titan rotorcraft could be used to perform a wide variety of different science missions, we have elected to focus *Dragonfly* on prebiotic chemistry, habitability, and a search for biosignatures. At Titan Through Time 5, we will describe the science we plan with *Dragonfly* [1,2], so that everyone better understands the mission capabilities and concept of operations and how your own research might fit in with the *Dragonfly* investigation.

Goal A: Our first science goal relates to the exploration of Titan's profuse carbon-bearing molecules: we seek to ascertain how far Titan's organics have progressed toward potential prebiotic chemistry. Because Titan possesses two liquid solvents in which chemistry might occur, we will explore the possibilities of organic chemistry in both liquid methane/ethane and in liquid water. *Dragonfly* will sample the organic sands near Selk Crater [3,4] with a mass spectrometer, which will measure organic molecules as large as the amino acid tryptophan (204 Da) [5]. We will also sample water-ice-rich solids to look for organic molecules in a more familiar aqueous environment.

Goal B, C, and D: Next we will assess aspects of Titan's potential habitability for both water-based and potential hydrocarbon-based life. In Goal B, we will determine the role of Titan's tropical atmosphere and shallow subsurface reservoirs in the global methane cycle. Our Goal C will provide context for our samples by evaluating their provenance, determining the rates of processes modifying Titan's surface and rates of material transport. And our final habitability goal, Goal D, will constrain when and where water and organics might mix at Titan's surface, within its crust, and in the subsurface ocean [6].

Goal E: Our final science goal is to perform a search for chemical biosignatures that may be present at Titan's surface. The ambitious scope afforded by the New Frontiers program allows us to look for patterns of molecular abundance, molecular chirality, and potential hydrogen sinks [7] that would show chemical evidence for extinct or extant self-replicating systems. This broad approach to the search for life takes a step back from looking for bugs directly in favor of instead looking for their chemical fingerprints – a more agnostic approach requiring fewer assumptions regarding the nature of what we might find in such an exotic extraterrestrial environment.

References: [1] Barnes et al. (2021) *PSJ,* in press. [2] Turtle et al. (2021) TTT5. [3] Soderblom et al. 2010 *Icarus* [4] Lorenz et al. 2021 *PSJ* [5] Trainer et al. (2021) TTT5. [6] Sotzen K & Lorenz D (2021) TTT5 [7] McKay& Smith (2005) *Icarus*

Mapping the formation and dynamics of C2H5CN, C2H3CN, HCN, and C3H8 from 2012 to 2017 with ALMA.

H. Barry[1], C. A. Nixon[2], A. E. Thelen[2,3], E. Garcia-Berrios[2,4], M. Palmer[2,4,5], M. Cordiner[2,4], S. Charnley[2]

After the end of the Cassini era, many questions pertaining to the formation and dynamics of complex organic molecules in Titan's atmosphere remain unanswered. The Atacama Large Millimeter/submillimeter Array (ALMA) in Chile provides high spectral and spatial resolution data in frequency ranges that are key to identifying new organic molecules in Titan's atmosphere, and studying variations in their distributions. Many observations of Titan are available in the ALMA Science Archive from 2012 to 2017, some of which are dedicated to Titan itself, while others are due to the use of Titan as a calibration object for other science targets. C_2H_5CN (ethyl cyanide) [1], C_2H_3CN (vinyl cyanide) [2], HCN (hydrogen cyanide) [3], and C_3H_8 (propane) [3] have previously been identified and mapped in Titan's atmosphere using ALMA, but a full temporal analysis of the emission maps of these gases, across all available archival datasets, has not yet been performed.

We examined archival observations of Titan, particularly those in ALMA Bands 6 and 7 (211 – 373 GHz) where the array is most sensitive to Titan's molecular emission, to produce maps of several organic molecules as snapshots of the moon between 2012 and 2017. In particular, we investigated the latitudinal molecular emission patterns to search for variations between the equator and poles. The measured variability provides clues regarding the formation and atmospheric transport of C_2H_5CN, C_2H_3CN, HCN, and C_3H_8 with time. We present a poster summarizing our maps of these molecules in context with previous measurements from Cassini and ALMA, and discuss their implications for Titan's atmospheric composition and dynamics during its northern spring and summer.

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TITAN'S ANNULAR MODES OF CLIMATE VARIABILITY COMPARED TO EARTH AND MARS. J. M. Battalio[1] and J. M. Lora[1], [1]Department of Earth and Planetary Sciences, Yale University, 210 Whitney Ave., New Haven, CT 06511, joseph.battalio@yale.edu

Introduction: Annular modes are zonally symmetric patterns of climatic variability that explain large percentages of the variance in zonal-mean wind, eddy activity, and precipitation on Earth [1,2]. Indications of annular modes have been shown on Mars too [3], which is expected given the similarity in their extratropical dynamics. Titan inhabits a distinct dynamical regime, where the extratropics are confined close to the poles; thus, it is not obvious that Titan should have similar annular variability. Here, we compare annular modes in the atmospheres of Earth, Mars, and Titan.

Methods: Empirical Orthogonal Function (EOF) analysis [4] defines the annular mode of the anomalous (non-seasonal) zonal-mean zonal wind ([*u*]) and eddy kinetic energy ([*EKE*] = $[u^{*2}+v^{*2}]/2$). Regressions of the modes onto the eddy heat flux $[v^*T^*]$ and eddy momentum flux $[u^*v^*]$ are also considered. Reanalyses are used for Mars (MACDA [5] and EMARS [6]). For Titan, a 20-Titan year simulation of the Titan Atmospheric Model (TAM) [7] is used that is re-initialized from simulations [8] using a surface hydraulic conductivity of $k=5\times10^{-5}$ m/s.

Results: Titan and Mars do indeed have annular modes of variability, just as Earth does [9]. The modes broadly share the same types of spatial structures as Earth's modes; however, the exact patterns and details elucidate differences in each world's climate.

Zonal-mean zonal wind. The annular mode in the [*u*] for Earth is barotropic, in that the mode connects with momentum fluxes and has a vertically stacked structure. The leading (first) pattern of spatial variability is a dipole with centers of action at 70N/S and 45 N/S [1,2]. This represents the movement of the jet stream north and south. For Mars, this is also generally the case. For Titan, the annular mode in [*u*] is also a dipole, but the centers of action are aligned vertically instead of horizontally, that is at roughly the same latitude but at 400 and 1000 hPa. This behavior reflects movement of the jet vertically, which is seen in previous simulations of Titan's climate [8]. Additionally, the amount of variance in [*u*] explained is ~68%, compared to only 20–30% for Earth and Mars. Titan's mode associates with eddy momentum fluxes, just as on Mars and Earth, but also regresses strongly onto eddy heat fluxes, which may indicate that the jet on Titan relies on barotropic and baroclinic processes.

Zonal-mean eddy kinetic energy. The annular mode in the [*EKE*] for Earth is baroclinic in that it links to heat fluxes but not momentum fluxes. It explains about 40% of the [*EKE*] variance and is mono-polar, representing the intensification of the storm track [2]. Mars's [*EKE*] mode resembles Earth's, but it does link to eddy momentum fluxes, revealing the interconnected nature of the baroclinic wave lifecycle on Mars [10]. Titan's annular [*EKE*] mode connects to eddy and momentum fluxes and, like Mars, explains a larger percentage of [*EKE*] variance (~40–60%). Despite the wide extent of the Hadley circulation on Titan, the [*EKE*] mode regresses most strongly onto the *EKE* at the same latitudes as that of Mars and Earth (Fig. 1). However, the order of magnitude of the regression is (10^3 J/m^2)—two orders smaller than Earth's mode.

The ubiquity of annular modes demonstrates the similarities between the climates of Earth, Mars, and Titan and will inform efforts to understand the variability of dust activity on Mars and methane precipitation on Titan, among other phenomena.

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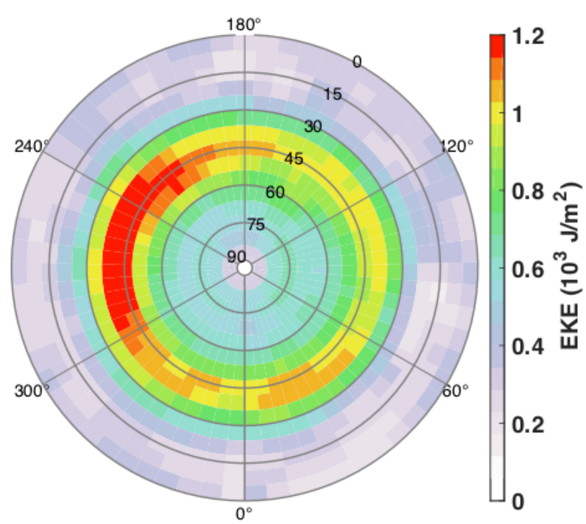

Fig 1. Annular mode in [EKE] for Titan.

RECONSTRUCTING RIVER FLOWS ON EARTH & TITAN. S.P.D. Birch[1], J.T. Perron[1], J.M. Soderblom[1], J.W. Miller[2], R. Palermo[1,5], P. Corlies[1], J. Lora[4], A.G Hayes[6], and A. Ashton[5], [1]MIT, [2]UCLA, [4]Yale, [5]WHOI, [6]Cornell

Introduction: Alluvial rivers are self-formed conveyor belts of sediment with predictable geometries reflective of their local climate and geology [1]. Such rivers, which flow across a mobile granular medium, are constantly adjusting to changing discharges forced onto them by the local climate [2]. Empirical hydraulic geometry relations allow for reconstruction of these dynamics and a better understanding of the climatic conditions under which these rivers have evolved [3].

Titan may also host alluvial rivers, enabling us to investigate its past or current climate using these same methodologies. In this presentation, we will show that hydraulic geometry relationships can be universally applied on Earth and Titan, utilizing only remote measures of channel width and slope. This permits calculations of bed grain size and the discharges of fluid and sediment. We will discuss the implications of these calculations for Titan's climate and make predictions for what *Dragonfly* may observe.

Dimensionless Hydraulic Geometry: For single-thread gravel-bedded rivers, Parker et al. [2] formulated dimensionless relations for the channel width, slope, depth, and sediment discharge. These relations rely on field measurements of the channel width, depth, slope, discharge, and median bed grain size.

To test the utility of these relations, we collate field measurements for 535 different terrestrial rivers. This enables us to calculate the dimensionless depth, slope and width for multiple river classes (e.g., sand, gravel, bedrock, etc.) from diverse climatic and geographic regions around the world. For each class of river, we then use a Monte Carlo technique to fit our dimensionless channel relations as power law functions of a dimensionless discharge [2]. This provides estimates and uncertainties for the empirical fits.

Unlike on Earth, where we can measure properties of rivers in the field, such as flow, sediment discharge or grain size, measurements of rivers on Titan are limited to what can be estimated from remote sensing data. Specifically, Cassini SAR images allow us to place bounds on channel width, while limited topographic data provide measures of channel slope [4].

Because of these limitations, we rearrange the Parker et al. [2] dimensionless equations so as to have channel width and slope as independent variables. We then solve for the median bed grain size (D_{50}), flow discharge (Q), and bedload discharge (Q_s).

Finally, we combine empirically fitted constants with a series of theoretical gravel sediment transport equations that prescribe how energy is dissipated within the flow, and how sediment is mobilized, to derive new density-dependent scaling coefficients. This provides an internally self-consistent means for application to Titan, and explicitly accounts for any hidden gravity or density coefficients often embedded in similar empirical relations.

Application to Titan's Rivers: We select the Vid Flumina and Saraswati Flumina drainage basins for study, two river networks on Titan for which slope can reliably be estimated.

We predict bed grain sizes ranging from D_{50}=3–9 cm at Vid Flumina to D_{50}=2–20 cm at Saraswati Flumina, similar to comparably sized gravel-bedded channels on Earth. Assuming that all the runoff from the upstream drainage area (A) goes into mobilizing sediment within a single active channel at a time, we estimate runoff rates ($M=Q/A$) of M<0.5–2x10^{-3} mm/hr at Vid Flumina, and M<0.1–5x10^{-1} mm/hr at Saraswati Flumen. Permitting losses to infiltration/evaporation, these rates are consistent with climate models [5].

From our estimates of the flow and sediment discharges, we find that the timescale to construct (V/Q_s) the possible river delta in Ontario Lacus is >3x10^4–5x10^7 hours of active flow time. For a range of plausible estimates of the intermittency and duration of discharge events, we estimate the timescale to construct the largest delta at Ontario to be ~10,000–700,000 Earth years.

Implications: Our predicted formation timescale for the Ontario deltas suggests that the Ontario deltas can form within a single ~10^5 year climate cycle [6]. Any north polar deltas may therefore be obscured due to rising sea levels, while southern deltas from previous climate cycles may have been re-worked.

Due to the far more buoyant sediment load on Titan, we also predict that a river on Titan may be substantially wider (~3–6x) and flatter (~2–4x) than an analogous river on Earth. In situ observations of an alluvial channel bed by *Dragonfly* would be able to test these predictions. For the same reasons, *Dragonfly* may also observe river gravels even in the interdune regions within its landing ellipse.

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Another look at Polaznik Macula: views from multiple angles to separate haze distribution from surface albedo. C. Blue Arm[1], E.F. Young[2], P.M. Corlies, and J.M. Soderblom[3] [1]Amherst College, cbluearm22@amherst.edu, [2]Southwest Research Institute, [3]Massachusetts Institute of Technology

Introduction: We use Cassini Cassini-Huygens Visual and Infrared Mapping Spectrometer (VIMS) spectra taken from flybys T53 through T76 to fit for haze and methane distribution around the region of Polaznik Macula on Titan. This region was chosen because there has been previous analysis of this region of Titan, and allows for validation of our findings.

Method: This work uses spectra obtained from multiple viewing geometries (emission, incidence, and phase angles) over the same footprint to distinguish haze scattering from surface albedo effects. To fit for haze, methane, and surface albedo, we use PyDISORT, a radiative transfer code developed to model Titan's atmosphere (Ádámkovics et al. 2016). Having multiple angles of emission allows us to constrain the vertical haze distribution. PyDISORT allows us to generate Jacobians for haze, methane, and surface albedo. We report on the surface albedo over a small region of Polaznik Macula in the methane windows at 1.6, 2.0, 2.7-2.8 and 4.9 microns, and compare our findings to the findings to Vixie et al. (2012) and to the ISS map of the same region. We are looking at variations over time from flybys T53 (occurring on April 20, 2009) to T76 (occurring May 8, 2011), a time frame spanning a storm event on Titan. We also intend to expand our viewing area, and use the PyDISORT code and our fitting function to determine methane, haze, and surface albedo at any given region of Titan covered by VIMS spectra. Recently, significant time has been spent updating PyDISORT code to allow us to find better fits for VIMS spectra, as one of our major issues was having VIMS spectra with large emission angles (ie, higher altitudes, or farther away from the horizon) having poor fits to PyDISORT generated spectra, likely due to an issue with the haze contribution.

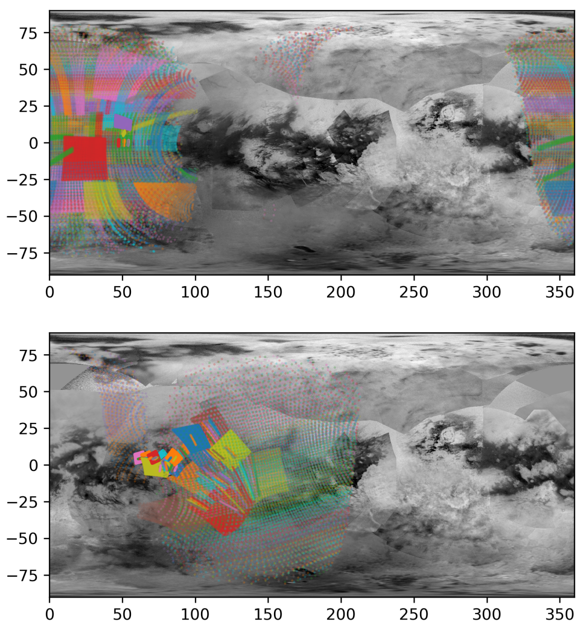

Figure 1. This figure shows two VIMS cube coverage maps, flybys T72 (April 5 2010) and T76 (May 8 2011), spanning a storm thought to occur around September 2010. One potential application of perfecting the usage of PyDISORT for fitting VIMS spectra will be to allow us to take a closer look at methane concentrations within the Titan atmosphere before and after storm events on Titan.

SURFACE PROPERTIES OF THE SELK CRATER REGION FROM SAR BACKSCATTER ANALYSIS.

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Introduction: The Dragonfly mission will explore the Selk crater region (6.5°N, 161.5°E), in the Shangri-la dune fields [1,2]. This region has been observed by several instruments onboard the Cassini spacecraft, with the Radar in Synthetic Aperture Radar (SAR) mode providing the highest resolution data of up to ~300 m/pixel. These data reveal a complex geomorphology, featuring a partially eroded, but geologically young, crater surrounded by reticulated and linear dune fields, radar-bright hummocky terrains, and undifferentiated plains that are at least partially composed of crater ejecta [3, 4].

Herein, we investigate the surface properties of various terrain types within the Dragonfly exploration area using overlapping SAR observations to construct backscatter curves, which express the observed normalized radar cross-section (NRCS) at multiple viewing geometries. The NRSC varies with incidence angle in different ways for different terrain units, depending on both the composition (dielectric constant) and the structure (surface roughness, grain size, and diffuse subsurface scattering) of the medium.

Method: The region of interest, which has been observed during 9 Titan flybys (T36, T39, T41, T61, T83, T95, T98, T120, and T121) has been mapped and divided into a 0.25° grid, following [2]. For each terrain unit, the SAR backscatter is averaged in each grid point and plotted versus incidence angle. Only grid points where the backscatter is uniform, without artefacts, and contains sufficient data points within the terrain unit are kept.

In order to derive surface properties for these terrains, we fit a model consisting in the sum of a quasi-specular component σ^0_{qs} (dominant below 20° incidence) and a diffuse volume scattering component σ^0_V (dominant above 30°). For the quasi-specular component, we use the Geometric Optics model, similar to [5], with the dielectric constant ε' and the rms slope s as parameters. The diffuse component simulates the scattering by discreet subsurface structures following [6], which also depends on the medium dielectric constant as well as the scattering albedo η.

Results: The best fits for each of the 5 terrain units are shown in Figure 1, with the parameters derived in Table 1. While the absolute values must be interpreted with caution (especially the dielectric constants above 3.15, corresponding to water ice) as they are model-dependent, the relative values show real variations in surface properties. The dune fields thus appear very smooth at the scale of the radar wavelength (2.2 cm), while their low dielectric constant and scattering albedo indicates an absorbing, organic composition. Meanwhile, higher dielectric constants and scattering albedos in the rim and ejecta point to the presence of water ice and buried scattering structures such as cracks, which may have formed during the impact.

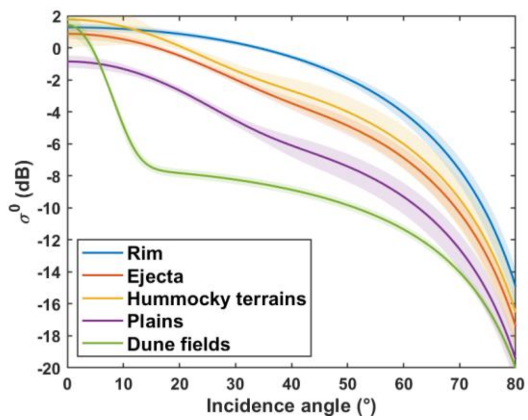

Figure 1: Best fit for each terrain unit near Selk crater, with 95% confidence intervals. The parameters of the fits are shown in Table 1.

Table 1: Best fit parameters for each terrain type shown in Figure 1. For the rim, the best fit includes only a diffuse component, and the rms slope cannot be determined.

	Rim	Ejecta	Hummocky terrains	Plains	Dune fields
ε'	4.0±1.4	3.3±0.4	3.3±0.7	2.8±0.3	1.71±0.02
η	3.4±0.5	1.6±0.06	1.9±0.2	0.79±0.07	0.37±0.02
s	-	11.0°±0.9	9.9°±2.6	10.4°±0.9	3.4°±0.2

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THE EFFECT OF TITAN'S ICE SHELL TEMPERATURE ON PRESSURE-DRIVEN ERUPTIONS. G. E. Brouwer[1], S. A. Fagents[1], L. S. Schurmeier[1], [1]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, Hawai'i 96822, USA (*gbrouwer@hawaii.edu).

Introduction: To investigate Titan's habitability, it is important to explore mechanisms that may transfer potential biosignatures from the subsurface to the surface where they may be detected by future missions. This work models the ascent of liquid through a fracture in the ice shell due to freezing and pressurization of a subsurface liquid reservoir under various thermal conditions. We extend a pressure-driven eruption model applied to resurfacing on Europa [3, 5] and calculate the volume fraction of liquid in the reservoir that must freeze in order to generate the critical reservoir pressure to produce an eruption. We find the time required for that degree of freezing to be achieved as a function of reservoir depth, volume, composition, and the thermal properties of the ice shell.

Model: *Freezing.* We assume a spherical liquid reservoir exists within the brittle portion of the ice shell (Figure 1), which we take to be 20 km thick [8]. We explore three liquid compositions: a 1.5 w.% NH_3-H_2O mixture, pure H_2O, and a 10 w.% $(NH_4)_2SO_4$ – H_2O mixture, listed in order of increasing density contrast with water ice ($\Delta\rho = \rho_{liquid} - \rho_{ice}$). We estimate the time necessary to freeze the critical volume of liquid by iteratively solving the Stefan problem, which provides the position of the phase change boundary as a function of time. We also estimate the amount of liquid erupted during one event using the initial reservoir overpressure and conservation of momentum assuming turbulent flow.

Temperature profiles. We explore different thermal profiles for a convective ice shell with an outer layer of methane clathrate (0, 5, and 10 km thick) in order to test the effects on reservoir freezing: (1) temperature profiles derived from PlanetProfile [7] in which the ice shell thickness is a dependent variable; and (2) temperature profiles from [4], in which the ice shell thickness is set at 100 km [4]. We choose two reservoir volumes, 0.5 km^3 and 500 km^3.

Results & Discussion: Freezing occurs on timescales of ~ 1 – 10^4 years increasing with depth and

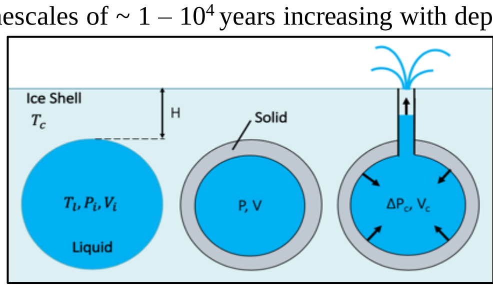

Figure 1. Illustration of the pressure-driven eruption mechanism. (1) Reservoir is cooled to its freezing temperature, (2) Freezing begins, pressure increases due to density contrast between liquid and solid phases, and (3) the pressure reaches critical point.

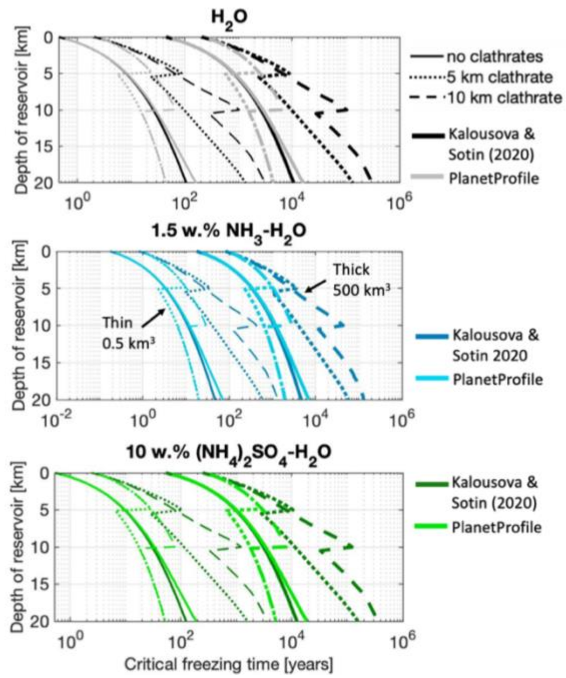

Figure 2. Time required for a freezing reservoir to reach the critical pressure necessary for eruption. Top: pure H_2O reservoir fluid; Middle:1.5 wt. % NH_3 – H_2O mixture; Bottom: 10 wt. % (NH$_4$)2SO$_4$ – H_2O mixture. Results are shown for six different ice shell temperature profiles and for two different reservoir sizes 0.5 km^3 (left set of curves) and 500 km^3 (right set of curves).

reservoir size. The addition of 1.5 w.% NH_3 increases the freezing time by ~20%. The addition of 10 w.% $(NH_4)_2SO_4$ decreases freezing times by ~50%. Reservoir sizes of 0.5 and 500 km^3 produce erupted volumes of 10^6 – 10^{10} m^3, comparable to potential flow features on Titan (10^6 – 10^{10} m^3) [1, 6]. The freezing times for a 5 and 10 km thick clathrate layer are shorter when using thermal profiles from PlanetProfile than those from [4]. This is because the warmer ice shells from [4] decrease the thermal gradient between the reservoir and ice, and hence increase freezing times. The low thermal conductivity of methane clathrate relative to ice leads to higher temperatures in the clathrate layer, which also increases reservoir freezing times. Future work will consider the compositional evolution of NH_3 and $(NH_4)_2SO_4$ in the freezing liquid.

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Dynamics of mixed clathrate-ice shells on icy ocean worlds Evan Carnahan[1], Steven D. Vance[2], Marc A. Hesse[1,3], Baptiste Journaux[4], and Christophe Sotin[5], [1]Oden Institute for Computational Engineering and Sciences, The University of Texas at Austin, Austin, TX, USA (evan.carnahan@utexas.edu) [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA [3]Department of Geological Sciences, The University of Texas at Austin, Austin, TX, USA [4]Department of Earth and Space Sciences, University of Washington, Seattle, WA, USA [5]Laboratoire de Planetologie et Geodynamique, Universite de Nantes, Nantes, France

Abstract: Ice shell dynamics regulate the cooling and transport of materials into and out of icy ocean worlds. Volatile clathrates are expected to constitute a large fraction of ice shells across ocean worlds. Previous work shows a methane clathrate layer at the surface of the ice shell of Titan thickens the convecting region [1], while on Pluto a clathrate layer at the base of the ice shell stops convection [2]. In this way, the dynamics of mixed clathrate-ice shells may be essential to the thermal evolution and habitability of ocean worlds. However, studies to date have not addressed the dynamics that determine the distribution of clathrates within the ice shell. Here we show that, in contrast to previous studies, clathrates are likely entrained throughout ice shells, and as such are integral to their dynamics. Entrained clathrates thicken the conductive lid and slow the cooling of Titan and Pluto, potentially preserving habitable environments. A general scaling of our results demonstrates that entrained clathrates may stop convection across a wide range of ocean worlds.

Clathrates are expected to be present and stable throughout most of the outer shell of a wide range of ocean worlds [3]. Due to their low density methane gas or clathrates will rise to the base of the outer ice shell. We find a buoyant flux of clathrates to the base of a convecting outer ice shell is continuously incorporated. The continuous incorporation of clathrates at the base of the ice shell entrains them throughout the convective portion of the ice shell (Figure 1d and e). The entrainment of methane clathrates throughout planetary evolution until present can thicken the conductive lid of Titan by over 60 km (Figure 1b and d) and may result in limited convection on Pluto (Figure 1e).

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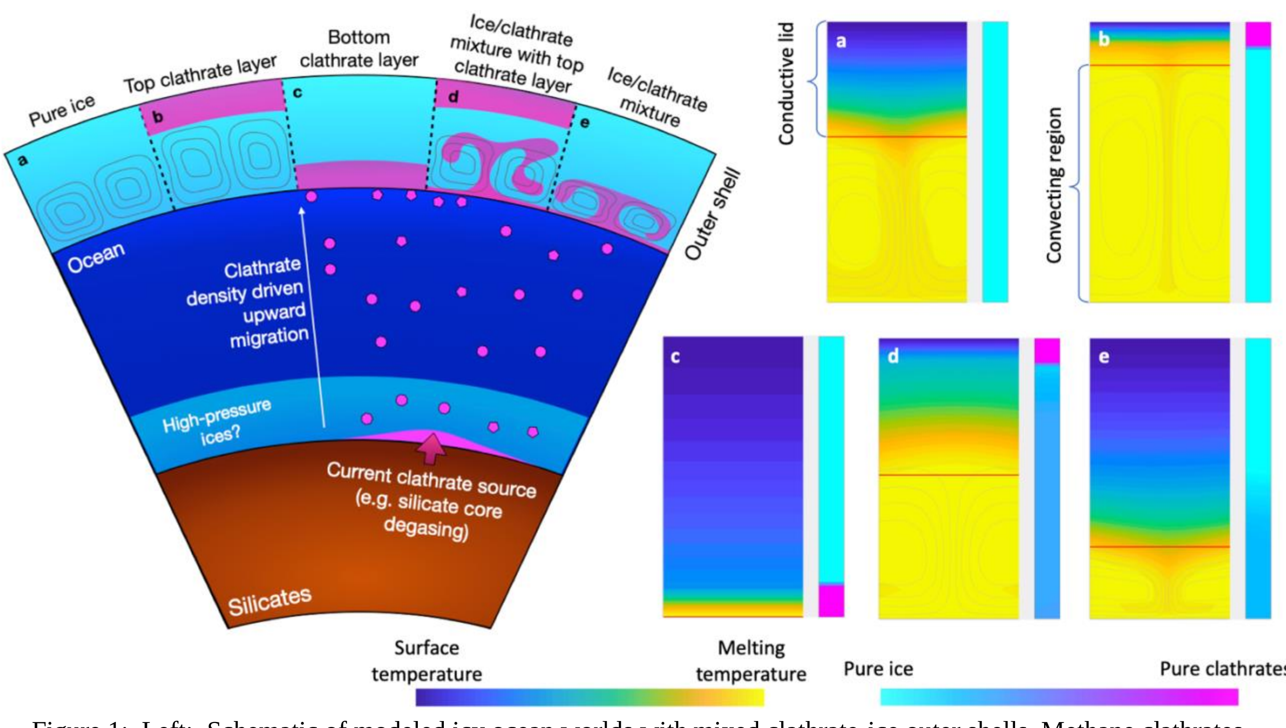

Figure 1: Left: Schematic of modeled icy ocean worlds with mixed clathrate-ice outer shells. Methane clathrates buoyantly rise and are entrained into the outer ice shell. Right: The corresponding thermal structures of mixed outer clathrate-ice shells are shown for (a) a pure-ice shell, (b) an ice shell with a surface methane clathrate layer, (c) a pure ice shell with a static basal clathrate layer, (d) a mixed clathrate-ice shell with a surface methane clathrate layer, and(e) a mixed clathrate-ice shell. For each, the average volume fraction of clathrate is plotted and the thickness of the conductive and convective regions are marked.

Aerosols-plasma interaction in the ionosphere of Titan. A. Chatain[1,2,3], N. Carrasco[1], L. Vettier[1] and O. Guaitella[2], [1]Université Paris-Saclay, UVSQ, CNRS, LATMOS/IPSL, Guyancourt, France (audrey.chatain@latmos.ipsl.fr). [2]Ecole polytechnique, Sorbonne Université, CNRS, LPP, Palaiseau, France. [3]Sorbonne Université, CNRS, LMD/IPSL, Paris, France.

Introduction: The Cassini mission discovered that Titan's famous orange aerosols start forming around 900-1200 km, in the ionosphere **[1]**. The ionosphere is the upper part of the atmosphere, ionized by UV solar photons and energetic particles from Saturn's magnetosphere. It therefore hosts reactive plasma species (electrons, ions, radicals, excited species) that are likely to interact with the newly formed aerosols.

We know that carbon-bearing species trigger the carbon growth of the aerosols. Nevertheless, the interaction of Titan's aerosols with the other 'carbon-free' plasma species has never been studied before. For this work, we designed a new experimental setup to study this interaction, observed the evolutions induced on the aerosols and the gas phase, and proposed evolution mechanisms at the surface of the grains.

The THETIS experiment: *THolins Evolution in Titan's Ionosphere Simulation*. The ionosphere of Titan 'free of carbon species' is simulated by a DC glow plasma discharge in N_2-H_2 (with up to 5% H_2). Analogues of Titan's aerosols (*tholins*) are previously formed in suspension in the plasma experiment PAMPRE **[2]**. They are then spread on a thin metallic grid, which is exposed to the N_2-H_2 plasma.

Evolution of the aerosols is monitored by *in situ* infrared spectroscopy and *ex situ* scanning electron microscopy. The gas phase (neutrals and positive ions) is continuously probed by a mass spectrometer whose transmittance has previously been finely determined **[3]** to enable a quantitative comparison between all the mass intensities.

Experimental results: *Morphological and chemical evolution of the tholin grains.* Tholins are physically eroded by the exposure to the plasma, showing erosive structures of 20 nm on the 300 nm-grains. Chemical functions of the material evolve, with the disappearance of isonitriles and unsaturated structures, and the formation of a new nitrile band **[4]**.

Changes in the gas phase composition. The aerosols erosion has a feedback effect on the composition of the gas phase. Ammonia (NH_3), which is formed in the N_2-H_2 plasma, decreases with the insertion of tholins. This suggests that ammonia or its precursors are consumed by tholins. On the opposite, we observed the production of HCN and other carbon-containing molecules, such as acetonitrile (CH_3-CN) and cyanogen (C_2N_2). Observations of positive ions give similar results, with the decrease of ammonia-related ions (NH_x^+), and the formation of new carbon-containing ions (related to HCN, acetonitrile and cyanogen, plus highly-unsaturated hydrocarbons).

Heterogeneous processes at the surface of the grains: From these results and previous heterogeneous chemistry modelling work in microelectronics **[5]**, we suggest in Figure 1 some surface processes. Radicals are likely to chemically react with the tholins. In particular, an interaction of tholins carbon atoms with the radicals N, NH and H leads to the formation of $HCN_{(s)}$ (adsorbed at the surface). In parallel, ion sputtering ejects fragments of tholins into the gas phase (like HCN). In addition, NH – which is fundamental in the production of NH_3 – is used at the surface of tholins to form $HCN_{(s)}$, and can then explain the decrease of NH_3.

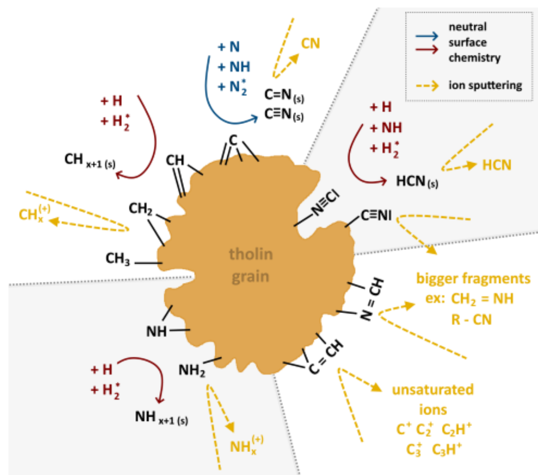

Fig 1. Suggestion of surface processes, as interactions between a tholin grain and N_2-H_2 plasma species.

Conclusion related to Titan: Though radicals are hard to detect in Titan ionosphere, models **[6,7]** predict that they are present in great quantity, and therefore could lead to the above mentioned processes. Actual chemical models in the ionosphere do not take heterogeneous chemical reactions into account, which will certainly be an interesting next step to try to explain the remaining discrepancies with Cassini observations.

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ALMA Observations of Rapid Temporal Variability in Titan's Upper-Atmospheric Winds.

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Titan possesses a system of super-rotating zonal winds that encircle the moon at speeds up to ~350 m/s. However, the origin of such fast, high-altitude equatorial winds is not yet understood. By linking the variability of Titan's zonal winds to seasonal atmospheric changes, we can test theories regarding the nature and temporal/spatial evolution of their driving forces.

Here we present results from remote sensing of Titan's atmosphere using the Atacama Large Millimeter/submillimeter Array (ALMA), focusing on the dynamics of the middle and upper atmosphere. In synergy with Cassini's end of mission (May 2017), we obtained high-resolution maps of the nitriles HNC, HC_3N, CH_3CN, and C_2H_5CN, which provide a powerful probe of Titan's atmospheric dynamics. As shown in Figure 1, spatially and spectrally resolved HNC observations reveal an unexpectedly-strong (47%) reduction in the thermospheric zonal wind speed over a relatively short period of nine Earth months (17 Titan days, from L_s = 82º to 90º), leading up to the northern summer solstice. Such rapid variability is consistent with dynamical instability of the high-altitude equatorial jet (first discovered by Lellouch et al. 2019 [1]), implying strong intermittency of its driving force. These changes in zonal circulation may be related to stochastic or seasonal variability in the latitudinal and vertical transport of angular momentum away from the winter polar vortex [2,3].

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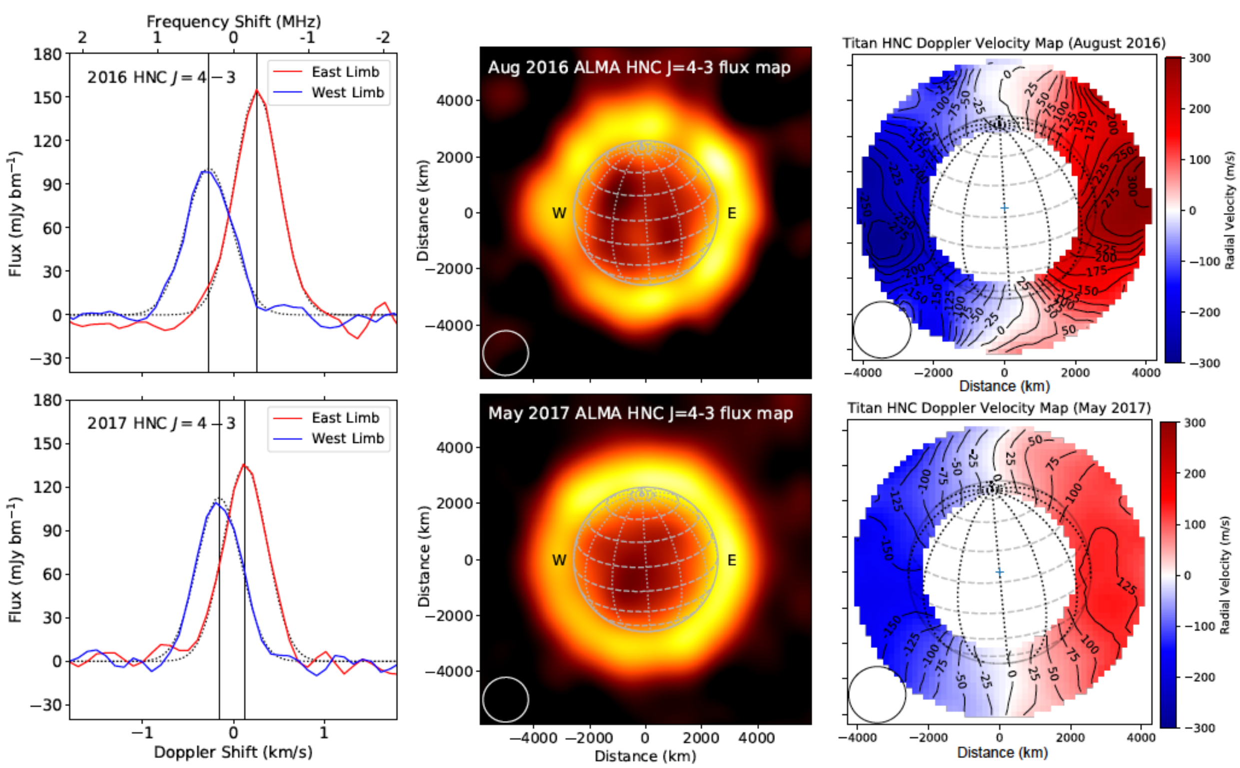

Figure 1: Left column – ALMA Band 7 HNC spectra observed at Titan's eastern and western limbs in August 2016 and May 2017. Line-of-sight wind velocities are marked with vertical dotted lines, revealing a 47% drop in zonal wind speed from 2016 to 2017. Center column – continuum-subtracted HNC emission maps. Spectra were extracted at the points labeled E and W, respectively. Right column – Line-of-sight wind velocity maps (contours are in units of m/s). See [1,3] for details.

TITAN'S METEOROLOGY AND CLOUDS: PAST OBSERVATIONS AND FUTURE FORECASTS. P. Corlies[*,1,2], A. G. Hayes[2], M. Ádámkovics[3,4], S. Rodriguez[5], E. P. Turtle[6], J. M. Lora[7], J. L. Mitchell[8], J. M. Soderblom[1], A. Soto[9], J. A. Kelland[2], P. Rojo[10], J. E. Perry[11], C. E. Newmann[12], J. I. Lunine[1], [*]Presenting author (pcorlies@astro.cornell.edu), [1]Massachusetts Institute of Technology, Cambridge MA, [2]Cornell University, Ithaca NY, [3]SETI Institute, Mountain View, CA, [4]Lockheed Martin Advanced Technology Center, Palo Alto, CA, [5]Université Paris-Diderot, USPC, Paris, France, [6]Johns Hopkins University Applied Physics Laboratory, Laurel MD, [7]Yale University, New Haven CT, [8]University of California, Los Angeles CA, [9]Southwest Research Institute, Boulder CO, [10]Universidad de Chile, Santiago, Chile, [11]University of Arizona, Tucson AZ, [12]Aeolis Research, Pasadena, CA

Introduction: Clouds are ideal diagnostic tools for understanding Titan's atmosphere and modelling its circulation and seasonality [1–3]. As the only other world with an active hydrologic cycle [4], clouds play a pivotal role in understanding the dynamics of Titan's atmosphere [5–7], the interaction between the surface and atmosphere [8–10], and the general circulation models of its complex climate [11–13]. In this talk, we overview our understanding of Titan's meteorology and clouds, beginning with the first detections of clouds [14] and ending with a discussion of observations in the coming decades.

Cassini Observations: *Cassini* observations provide invaluable insights into the location, frequency, and evolution of Titan's clouds. The *Cassini* Instrument Science Subsystem (ISS) offered unparalleled spatial imaging allowing for the identification of small clouds and accurate tracking of cloud speeds. *Cassini* Visual and Infrared Mapping Spectrometer (VIMS) spectral observations permit detailed modelling of cloud properties and evolution [15,16]. Together, these data have shaped our understanding of Titan cloud formation [15,16], precipitation [8,17], and atmospheric dynamics [1,5,15]. Herein, we present an analysis of Titan's clouds and the insights they offer into Titan's meteorology. We provide an analysis of the clouds observed with VIMS, discuss possible cloud formation mechanisms, and provide comparisons with general circulation model for cloud location, frequency, and intensity predictions. Combining these results with ISS observations of Titan's clouds [2,3], we discuss our knowledge of Titan's meteorology, both what we have learned through the *Cassini* mission [1,5,15,16], and the mysteries that remain on both local and global scales.

Ground Based Observations (GBOs): GBOs provided the first glimpses into Titan's meteorology with the earliest identification of clouds [14]. With the development of adaptive optics (AO) in the early 2000's, we obtained the images of resolved storms on Titan [18,19]. Complementing *Cassini* observations, continued monitoring demonstrated a seasonality to Titan's clouds that offered one of the first glimpses into the dynamics that drive Titan's atmosphere [1,20,21]. Thus, GBOs have been fundamental in shaping our understanding of Titan's meteorology. Building on decades of observations, we present the results of an ongoing monitoring campaign of Titan's clouds. This campaign upholds the legacy of the *Cassini* mission by monitoring Titan's weather through northern summer solstice, and will complete one Titan year of observations in 2027. After an unexpected delay, violent storms have been observed at northern mid-latitudes at an enhanced rate compared to the south [18,19], suggesting a seasonal asymmetry. Given the concentration of surface liquid in the North, monitoring Titan's weather through northern summer will provide critical insights into the connection between the surface and lower atmosphere.

Future Forecasts: With the end of the *Cassini* mission, we now rely on GBOs to observe Titan's meteorology. The next generation of telescopes, such as the ELT (39m, planned 2025), the TMT (30m, planned 2027), and the GMT (24.5m, planned 2029), will continue to improve the Earth-based observations of Titan. In addition, the Dragonfly mission (planned 2034) will provide new sampling of Titan's atmosphere [22], improving upon the measurements of the Huygens probe, which still remain the only *in situ* "ground truth" for models.

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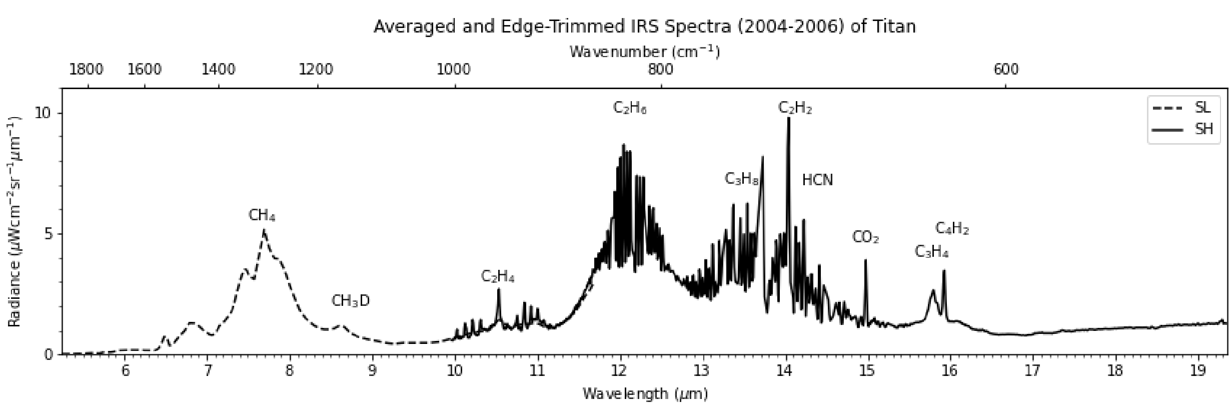
Compositional Analysis of Titan's Atmosphere Using Spitzer Infrared Spectrograph Data Brandon Park Coy[1,2], Conor A. Nixon[2], Naomi Rowe-Gurney[3], Richard Achterberg[1,2,4], Leigh N. Fletcher[3], and Patrick Irwin[5] [1]Center for Research and Exploration in Space Science & Technology, [2]Planetary Systems Laboratory, NASA Goddard Space Flight Center, [3]School of Physics and Astronomy, University of Leicester, [4]Department of Astronomy, University of Maryland, [5]Department of Physics, University of Oxford

Introduction: We present, for the first time, infrared spectra from the Spitzer Space Telescope's Infrared Spectrograph (IRS) (2004-2008) [1] of Titan in both the short wavelength-low resolution (SL, R=60~127, 5.13-14.29 μm) and short wavelength-high resolution (SH, R=600, 9.89-19.51 μm) channels showing the emissions of CH_4, C_2H_4, C_2H_2, C_2H_6, HCN, CO_2, HC_3N, C_3H_4, C_4H_2, and C_3H_8.

Spitzer IRS data has been used to measure atmospheric composition of various Solar System bodies, including Neptune [2] and Uranus [3][4]. Although Spitzer took multiple dedicated observations of Titan, none of the results have been modeled before. We conduct our own investigation of these datasets and search for new results.

We retrieve temperature and gas composition profiles using the Non-linear Optimal Estimator for MultivariatE Spectral analySIS (NEMESIS) planetary atmosphere radiative transfer and retrieval tool [5] and compare the results obtained for Titan to those of the Cassini Composite Infrared Spectrometer (CIRS) and the Infrared Space Observatory Short Wavelength Spectrometer [6], and comment on the effect of spectral resolution on retrieved information content.

We conclude by recommending gaps in current spectroscopic knowledge of molecular bands that could be addressed by theoretical and laboratory study to aid future astronomical studies of Titan, for example the James Webb Space Telescope (JWST) and the Stratospheric Observatory for Infrared Astronomy (SOFIA)



Acknowledgments: Data analyzed in this project is public available online on the Spitzer Heritage Archive (sha.ipac.caltech.edu). This research has made use of the NASA/IPAC Infrared Science Archive, which is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology. Coy and Nixon were funded by the NASA Astrobiology Institute. Rowe-Gurney was supported by a European Research Council Consolidator Grant (under the EU's Horizon 2020 research and innovation program, grant agreement No. 723890) at the University of Leicester).

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CONSTRAINTS OF THE FORMATION OF MENRVA CRATER: ASTROBIOLOGICAL IMPLICATIONS. A.P Crósta[1]; E.A. Silber[2], R.M.C. Lopes[3], M.J. Malaska[3], A. Solomonidou[4], B.C. Johnson[5], S.D. Vance[3], C. Sotin[6], E. Bjonnes[7], J.M. Soderblom[8] [1]Geosciences Institute, State University of Campinas, P.O. Box 6152, 13083-970, Campinas, SP, Brazil crosta@unicamp.br; [2]Western University, London, ON, Canada; [3]Jet Propulsion Laboratory, California Institute of Technology; [4]California Institute of Technology; [5]Purdue University; [6]University of Nantes, France; [7]Brown University; [8]Massachusetts Institute of Technology

Introduction: Menrva is the largest impact crater on Titan, with ca. 425 km diameter. Its formation represents a geological event of significant consequences that likely happened in the last billion years of Titan's history. Very large craters are prone to have formed earlier in the geological history of the solar system. However, the degree of preservation of Menrva's main morpho-structural features, considering, suggests a younger age [1].

We report on simulations of the Menrva impact event and its physical constraints. Through numerical modeling, we establish constraints for temperature, pression, extents of melt formation in both, lateral and vertical directions, and potential materials exchange among Titan's layers. Among other implications, we examine the role of such massive impact event in promoting habitable environments on Titan.

Modeling the formation of Menrva crater: The reasoning behind our models is that, given a large enough asteroid impact, the ice shell that forms the external layer of Titan's structure would be breached, either entirely or partly, creating pathways connecting the organic-rich mantle that covers its surface, to the sub-surface water ocean.

In the event of an ice shell breach, materials from the deep subsurface ocean, including salts and potential biosignatures of putative subsurface biota, could be emplaced on the surface — likewise, atmospherically-derived organics could be directly injected into the subsurface ocean, where they could undergo aqueous hydrolysis and form potential astrobiological building blocks.

To study the formation of a Menrva-like impact crater, we performed numerical simulations using the iSALE-2D shock physics code. We simulated different scenarios using current estimates of Titan's ice shell's thickness, constrained by the minimum and maximum values of 50 and 125 km, based on geophysical data [2,3]. We also use different thicknesses for the conductive ice lid (22 and 60 km), and temperatures for the convective ice layer (245 and 255 K). A combination of these parameters, plus impactor sizes (28 and 34 km diameter) and the vertical component of the impact velocity (10 and 7 km/s, respectively), resulted in 28 different scenarios tested, all producing a ca. 425 km diameter crater.

Results: In most of the scenarios, there was a complete breach of the ice shell at ca. 6000 s, except for the cases of a thicker shell and conductive ice lid (i.e. 125 and 60 km thick, respectively). In some, the penetration happened as melt-through into the ice shell.

Regarding the analysis of provenance depths, near surface materials are clearly mixed to great depths and vice versa. A considerable volume of ocean water is deposited within the crater, particularly in the center of the newly formed crater. Likewise, the surficial layer of organics, mostly methane, gets mixed with ice, undergoing complete or partial melt in the central region.

We also used tracers for the trajectories of parcels of the surficial organic layer, ice shell and water ocean. The results show that melt materials, including organics and water, reach ca. 100 km into the ocean underneath the center of the crater, whereas a mix of complete and partial melt reach 65 km depth and 60 km away from the center. There is also a organics/ice mixing at ca. 10 km depth and >200 km from the center, where the partly melted ice shell with a thin layer of melt materials overturns and bury the organic-rich layer, being covered by a ca. 5 km thick ejecta material.

Our modelling indicates that material mixing may take place on the surface and in the deep-water ocean, implying that both are suitable for putative biosignatures, either emplaced directly from subsurface mixing, or resulting from a transient surface habitat created by the impact. Similar results may be expected for craters with diameters in the range 70 to 120 km. In conclusion, large impact craters are preferred sites for future investigations of habitable environments on Titan.

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CHARACTERIZING THE NEAR-INFRARED SPECTRAL PROPERTIES OF ACETYLENE-BENZENE AND ACETONITRILE-ACETYLENE CO-CRYSTALS. E. C. Czaplinski[1], X. Yu[2], K. Dzurilla[1], V. F. Chevrier. [1]University of Arkansas, Center for Space and Planetary Sciences, Fayetteville, AR 72701. [2]Earth & Planetary Sciences Department, UCSC, Santa Cruz, CA 95064 (ecczapli@uark.edu).

Introduction: Interactions between solar UV rays and Titan's N_2/CH_4-dominated atmosphere generates a wide variety of organic compounds, such as acetylene (C_2H_2), benzene (C_6H_6), and acetonitrile (CH_3CN) [1-3]. C_2H_2 is one of the most abundant photochemical products in Titan's atmosphere [4], and has been detected both in situ [5] and spectrally [6]. C_2H_2 may be linked to the molecular composition of Titan's dunes [7,8], it is a primary candidate for comprising Titan evaporite deposits [9], and plays a major role in co-crystal formation [e.g., 10,11]. Another prominent compound, C_6H_6 forms co-crystals with C_2H_6 at Titan-relevant temperatures [12,13] and is also a probable evaporite material [14]. CH_3CN is a potential candidate for explaining the 5.01-µm VIMS feature [15].

Here, we investigate the C_2H_2-C_6H_6 and CH_3CN-C_2H_2 co-crystals at Titan temperatures and pressure using FTIR spectroscopy.

Methods: All experiments were performed in the University of Arkansas' Titan surface simulation chamber, which maintains Titan-relevant temperature and pressure [16]. Here, we use a "cold trap" method [17] for a more straightforward approach to introducing these compounds to the chamber.

C_2H_2-C_6H_6 Co-crystal: In repeated experiments, we observe co-crystal formation below 135 K (temperature range of the orthorhombic phase of C_2H_2) within minutes, and the co-crystal is stable at Titan surface-relevant temperatures (~93-94 K) [18]. The most prominent evidence of co-crystal formation is the appearance of new spectral bands from 1.569 to 1.598 µm and 1.943 to 2.122 µm (Fig. 1). Additionally, several bands shift upon co-crystal formation, and we observe drastic changes to the sample morphology (more structure to the sample) upon co-crystal formation.

CH_3CN-C_2H_2 Co-crystal: The co-crystal formed between 118 K and 174 K in repeated experiments and is stable at Titan surface-relevant temperatures. Changes in C_2H_2 bands may indicate phase trapping of the warmer cubic phase at colder temperatures. Upon co-crystal formation, we observe a new band at 1.676 µm (Fig. 1), band shifting/splitting, and changes to sample morphology that indicate crystal structure changes.

Conclusions: The relatively quick formation of co-crystals under Titan conditions implies that these molecular minerals may be common on Titan's surface. Co-crystallization of C_2H_2-C_6H_6 may be possible in Titan's stratosphere (~130-140 K) [18]. C_2H_2 and CH_3CN have been associated with Titan's dunes and dark terrains near the equator [15], representing the potential for co-crystal characterization by *Dragonfly*.

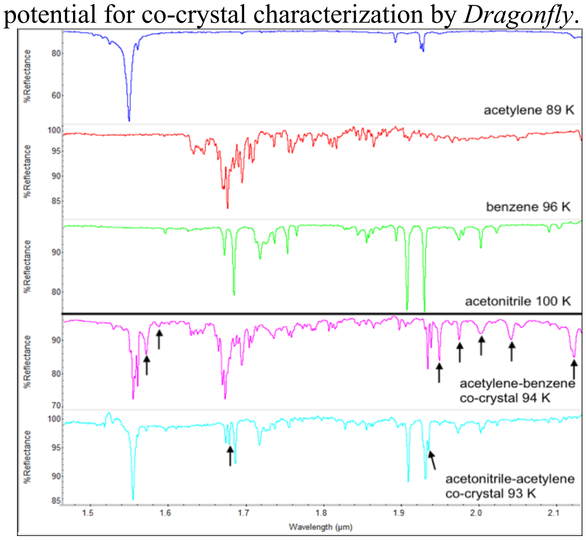

Figure 1. FTIR spectra of pure compounds (above black line) compared to co-crystal spectra (below black line). Limited wavelength range shown for clarity. Min/max y-axis values of each spectrum are normalized to a common scale. Notice the new co-crystal bands denoted by arrows.

Acknowledgement: This work was supported by NASA Headquarters under the NASA Earth and Space Science Fellowship Program – Grant #80NSSC17K0603.

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PROSPECTS OF CRYOVOLCANIC COLUMNAR JOINTS ON TITAN R. D. Dhingra[1] and M. Heslar[2], [1]Jet Propulsion Laboratory, Caltech, CA (rajani.dhingra@jpl.nasa.gov), [2]University of Idaho, Moscow, ID (astrophysicist@rocketmail.com)

Introduction: Columnar joints in basaltic rocks are hexagonal cooling cracks formed by slow cooling and subsequent contraction of erupted lava on the surface [1]. Basaltic columns are a common volcanic feature on Earth, and were even observed on Mars [2]. Experimental studies suggest columnar jointing occurs in corn starch [3] and glassy water ice [4].

While the basaltic columns are a result of cooling contraction, ice expands when it cools. This property of water-ice might limit column formation on cryogenic worlds, like Saturn's largest moon Titan. Does the cooling cryo-lava result in cryo-columns or cryo-pillow (like terrestrial pillow basalt) structure [5] is the goal of our study. We investigate the prospects of 'cryo-column' formation on Titan using the heat equation and analytical techniques from basaltic column observations [6].

The Cassini mission revealed the presence of ample surface hydrocarbons and several geological features possibly associated with cryo-volcanism on Titan [7]. The role of liquids in the cooling of lava plays a major role in the formation of columns on Earth and Mars. The presence of surface liquids intruding the cracks of cooling cryo-columns, might lead to faster surface cooling as discussed in. The presence of these surface liquids on Titan is the key distinction that may make Titan the most likely cryogenic world to host cryo-columns!

Probable cryovolcanic features on Titan include Sotra Patera, a deep-walled crater with a likely volcanic origin. Cryovolcanic regions may contain columnar joints or columns of impure water ice or other exotic ices, similar to the basalt columns observed at volcanic and cratered regions of Earth and Mars. Cryovolcanic sites could also be important for bringing up the deeper ocean-based organics [8] or pre-biotic chemistry on the surface.

A slush generated by a high speed impactor might cool similarly where the surface liquids might play a key role in cooling the slush into a cryo-pillow or a cryo-column. Selk Crater – the probable landing site for Dragonfly [9] could host something similar for a hypothesis testing especially since the Martian basaltic columns were discovered in a crater.

Given the formation of columnar joints observed on multiple planetary bodies and in various substances, we propose to explore the possibility of 'cryo-columns' on the ice and liquid-rich surface of Titan.

Scenarios: Cooling is an advective-diffusive process. The diffusive process orchestrates such that the thermal stresses exceed the material strength triggering cracks. At the same time, liquid intrusion into cooling cracks of column induce advection that results in faster cooling. The cooler temperature on the surface of Titan as compared to the subsurface will solidify the cryo-lava. However, this solidifying cryo-lava will expand unless it is quench cooled. [4] discovered that quench cooling colloidal suspensions in bulk water using liquid ethane does induces columnar jointing in the glassy ice.

The impactors poking the surface of Titan might provide this sudden change in temperatures. This impact melt might also quench cool and solidify into cryo-columns. In this scenario, we might have cryo-columns with impact origins as compared to volcanic origins.

Methods: We find that at the surface temperature and pressure conditions of Titan (94K and 1.5 atm) LDA (Low Density Amorphous) ice is the most stable form of ice. We first determine if the thermal strength of LDA ice is higher than its mechanical strength to initiate cracking in the cooling cryo-lava.

Then we use the 1D diffusion or heat equation to study how the temperature of a dry (zero soil moisture) cryo-column under Titan conditions might evolve over time.

Results: We compare the mechanical strength of pure ice and the thermal stress expected for a cooling 32% peritectic ammonia-ice cryo-column from 100-160 K. We find thermal cracking may be restricted to the near-surface since the thermal stress is the same order-of-magnitude as the mechanical strength at 100 K. Cryo-columns may grow up to 10-20 m if they are able to cool over a Titan year.

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INVESTIGATING THE CONDENSATION OF BENZENE (C_6H_6) IN TITAN'S SOUTH POLAR CLOUD SYSTEM WITH A COMBINATION OF LABORATORY, OBSERVATIONAL AND MODELING TOOLS.

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Background: We have combined laboratory, modeling and observational efforts to investigate the chemical and microphysical processes leading to the formation of the cloud system presenting C_6H_6 ice spectral signature [1] that formed at unusually high altitude (> 250 km) over Titan's South pole after the northern spring equinox. We present here a study focused on the formation of C_6H_6 ice clouds at 87ºS. We have measured, for the first time, the equilibrium vapor pressure of pure crystalline C_6H_6 at low temperatures (134-158 K), representative of Titan's atmosphere[2]. We have used our experimental results along with temperature profiles and C_6H_6 mixing ratios derived from Cassini Composite Infrared Spectrometer (CIRS) data as input parameters in the coupled microphysics radiative transfer Community Aerosol and Radiation Model for Atmospheres (CARMA)[3] in order to better constrain the microphysical formation of this cloud system.

Methods: In order to measure the C_6H_6 vapor pressure at Titan-relevant temperatures, we have used the Atmospheric Chemistry Laboratory at NASA Ames Research Center[4]. The experimental apparatus (Fig. 1) consists of a mounted silicon wafer at the end of a LN_2-cooled cryostat inside a cryogenic vacuum chamber. Once the substrate was cooled to Titan-like temperatures, benzene vapor was introduced. By incrementally adjusting the temperature (measured with thermocouples) and continuously acquiring IR spectra, we were able to determine the equilibrium vapor pressure (i.e. the pressure of C_6H_6 gas at a given temperature for which benzene ice is stable, neither growing nor desorbing) from 134-158 K.

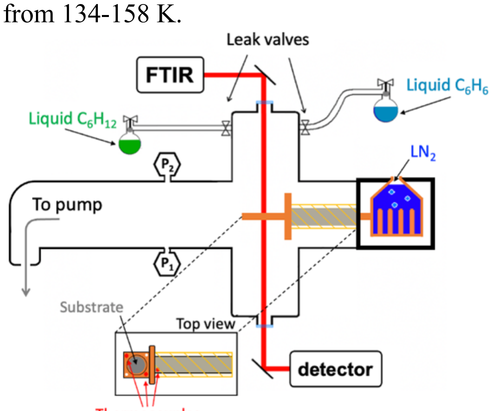

Figure 1. Schematic diagram of the experimental apparatus used for benzene ice condensation and growth studies (adapted from Iraci et al., 2010). Inset shows a top view of the sample holder.

Results: Our experimental measurements[2] show that the C_6H_6 vapor pressures at cold temperatures are higher than the extrapolations[5] most recently used for the analysis of Titan's observational data and in microphysics models (Fig. 2).

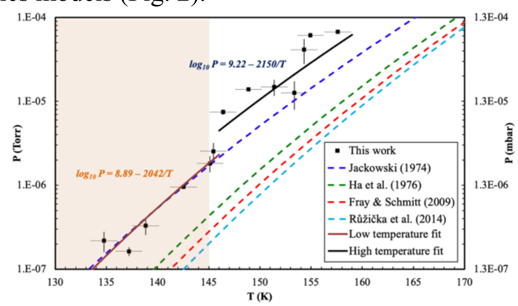

Figure 2. Experimental vapor pressure measurements of C_6H_6 ice (black) along with cold and warmer temperature parameterizations. For comparison, extrapolations from other parameterizations obtained in the literature are represented (Dubois et al. 2021[2], Fig. 5).

Using these new experimental vapor pressures in the CIRS and CARMA analyses results in benzene condensation occurring at lower altitudes in the stratosphere at 87ºS than previously determined. The CARMA simulations predict greater C_6H_6 gas mixing ratios below the condensation level than with previous vapor pressure extrapolations (~1000x higher), resulting in more C_6H_6 being available per cloud particle to condense at stratospheric levels (< 250 km) and hence a growth in size distribution, in particular between 125 km and 50 km. At 87ºS, as observed with the CIRS data re-analysis, the CARMA model predicts benzene condensation occurring deeper in the stratosphere. From the re-analysis of Cassini CIRS observations at latitudes spanning from 68ºS to 87ºS, we also inferred that the vortex polar boundary in 2013 resided between 78ºS and 83ºS. From 83ºS to 87ºS, the cloud top would be located between 246-256 km, and from 68ºS to 78ºS it would be located between 90 and 110 km.

Acknowledgments: This research is supported by NASA SMD's CDAP. The authors acknowledge outstanding technical support of E. Quigley.

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NEGATIVE ION CHEMISTRY IN TITAN'S UPPER ATMOSPHERE: MODELING EFFORTS TO ADDRESS CASSINI CAPS-ELS OBSERVATIONS. D. Dubois[1], A. W. Raymond[2], E. Sciamma-O'Brien[1], E. Mazur[3], and F. Salama[1] [1]NASA Ames Research Center, Moffett Field, CA, USA (david.f.dubois@nasa.gov), [2]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, USA, [3]Harvard University, Cambridge, MA, USA.

Background: The detection and measurements of heavy molecular anions in Titan's upper atmosphere represents one of Cassini's most unexpected discoveries. The Cassini Plasma Spectrometer Electron Spectrometer (CAPS-ELS) measurements from 16 passes more than 10 years ago revealed the presence of anions with mass-to-charge ratios >10,000[1]. These observations enabled the community to incorporate anion species in photochemical models in order to improve our understanding of the gas phase ion-neutral coupling as well as the formation and growth of macromolecular particles at high altitude (> 900 km). Subsequently, the first ionospheric photochemical model including negative ion species was developed[2], taking 11 low-mass anions into account. In spite of the lower-mass resolution of CAPS, comparison of the model outputs with CAPS data predicted CN^-, C_3N^- and C_5N^- to be the three most abundant negative ions with densities peaking near 1000 km[2]. However, the chemical composition and pathways leading to the formation of anion products still remains largely unknown.

Introduction: Photochemical modeling studies[3,4,5] and laboratory analog experiments have sought to account for negative ion species. Laboratory experiments have thus far mainly explored specific anion growth routes involving CN^- and C_3N^- [6,7,8], or negatively charged aromatic species with N and O atoms[9]. Recent multi-approach analyses have helped characterize observed mass peaks and growth patterns in relation to N-based ion reactions[10,11,12], while peculiar species such as $C_2N_3^-$ were reportedly identified as potential intermediate precursor seeds in the polymeric growth of laboratory-produced tholins, analogs of Titan's atmospheric haze particles[13,14,15]. Laboratory studies in support of the Cassini mission have also provided details on anion reaction rates[6,7] and their implication on high-altitude particle formation.

Here, we present an ongoing numerical effort to characterize Titan's upper atmosphere negative ion chemistry as part of a multi-disciplinary approach combining experimental simulations, plasma modeling and a comparison to the observational Cassini CAPS-ELS dataset.

Methods: This work relies on the further development of a chemical network model aimed at simulating the plasma chemistry in the Titan Haze Simulation (THS) experiment on the NASA Ames COSmIC facility[16, 17]. The THS facility uses a pulsed glow discharge plasma to simulate Titan's ionospheric chemistry at low Titan-like temperature. A fluid mechanics-based framework was developed to model the THS plasma and its truncated chemistry in the active region of the plasma discharge[17] (Fig. 1). It assumes a one-dimensional flow and tracks the evolution of reaction products in space and time. Building on earlier reaction pathways involving neutrals and positive ions, the ongoing study addresses new precursors[3] as well as negative ion chemistry to investigate their formation in the THS.

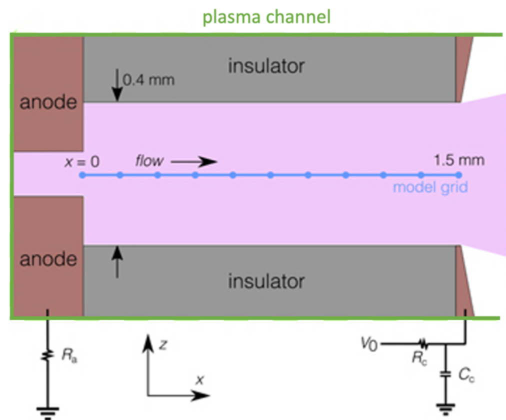

Figure 1. Geometry of the pulsed discharge nozzle used in the model, with the 1D grid along which the spatial derivatives are calculated (in blue) (adapted from [17]).

These recent developments and some preliminary results will be discussed in the context of the post-Cassini era and the need for synergistic laboratory and theoretical studies.

Acknowledgments: This work is supported by the NASA Postdoctoral Program and the NASA SMD SSW R&A Program.

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MAPPING THE CHANGE IN TEMPERATURE OF THE METHANE-ETHANE FREEZING POINTS WITH THE ADDITION OF NITROGEN AT CONSTANT VAPOR PRESSURE A. E. Engle[1,2], J. Hanley[2,1], S.P. Tan[3]. [1]Northern Arizona University (anna.engle@nau.edu), Flagstaff, AZ, [2]Lowell Observatory, Flagstaff, AZ,[3]Planetary Science Institute, Tucson, AZ.

Introduction: Recent work in Northern Arizona University's Astrophysical Materials Lab mapped the methane-ethane (CH_4-C_2H_6) phase diagram at low temperatures and pressures using Raman spectroscopy [1]. With the completion of this work, we have begun identifying the temperature at which ice first appears when nitrogen (N_2) is added to the binary system at ~1.4 bar. A previous study by [2] examined the dissolution of N_2 into CH_4-C_2H_6 mixtures and demonstrated that N_2 has a higher tendency of dissolving into the hydrocarbon (HC) mixture when it is introduced into CH_4-rich mixtures at lower temperatures and higher pressures. The work conducted in the Astro Mat Lab builds on this by mapping temperature changes in the phase transitions caused by the introduction of N_2. The intent of this work is to gain insight into potential processes occurring in the lakes and seas at Titan surface conditions.

Experimental Procedure: The system is located in the Astrophysical Materials Laboratory at Northern Arizona University [1, 3]. CH_4 and C_2H_6 are first mixed as room temperature gases. The sample cell is cooled to 95 K and the gas mixture is then released into the cell. The system is then further cooled to 90 K, at which time the cell is pressurized to ~1.4 bar by introducing N_2. The sample is allowed to settle for 20 minutes between each temperature step.

Due to dissolution rates, more N_2 must be added to the sample with increasing CH_4 concentration and decreasing temperature in order to maintain constant vapor pressure. While this does change the liquid composition of the sample as the experiment progresses (Figure 1), the total HC ratio remains the same and is tracked on the pseudo binary phase diagram shown in Figure 2, where each point has its own N_2 amount. Raman spectra and temperature measurements are also collected.

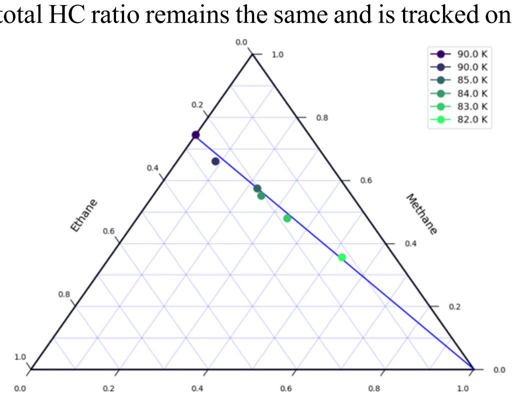

Figure 1. Example of N_2 dissolution into a starting CH_4-C_2H_6 mixture of ~0.75 CH_4. The first 90 K sample is the starting HC ratio and the second has N_2 added. The blue lines represents the constant HC ratio as N_2 is added and, as seen, decreasing temperature results in an increase of N_2 in the liquid. This HC ratio formed ice after the vapor-liquid equilibrium disappeared and is therefore not present in Figure 1.

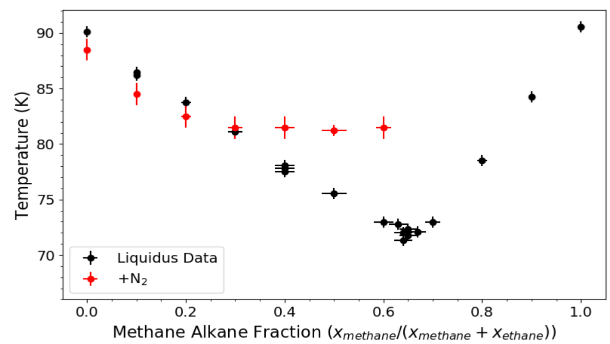

Figure 2. Comparison of CH_4-C_2H_6 liquidus curve (black dots) to the temperatures of the first appearance of ice when N_2 is isobarically added to the system at ~1.4 bar (red dots).

Results: Figure 2 is a comparison of the data collected thus far. We find that C_2H_6-rich mixtures up to ~0.2 CH_4 HC ratio exhibit a consistent freezing temperature depression in comparison to the binary liquidus. The trend then transitions to a flat line of approximately 81.5±0.5 K. Past ~0.6 CH_4 HC ratio, the vapor-liquid equilibrium is no longer sustained and we therefore cannot record a vapor pressure in the cell.

Future Work: Using models created with CRYO-CHEM 2.0 [4] as a guide, we have found that phase transitions are more sensitive to pressure changes than expected; in as small of a range as 0.1 bar. We have seen this effect in the lab, and it is likely due to the ease in which N_2 dissolves into the CH_4-C_2H_6 system with increasing pressure. With this in mind, we will enhance our experiments by mapping the temperatures of first ice at both 1.4 and 1.47 bar at each HC mixing ratio to better capture the potential processes occurring on Titan.

Given our previous findings that C_2H_6-rich HC mixtures tend to experience supercooling, we will determine whether C_2H_6-rich first ice occurs at higher temperatures when given more time to settle. Once we have completed this work, we will begin adding propane to the system to further map the temperature at which first ice appears.

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AN EXPERIMENTAL STUDY OF FLOATING LIQUID DROPLETS ON THE SURFACE OF LIQUID HYDROCARBONS. K. K. Farnsworth[1], A. Soto[2], J. K. Steckloff[3,4], V. F. Chevrier[1], J. M. Soderblom[5]. [1]University of Arkansas (farnsworth.kendra@gmail.com), [2]Southwest Research Institute, [3]Planetary Science Institute, [4]University of Texas at Austin, [5]Massachusetts Institute of Technology.

Introduction: Floating liquid droplets, or non-coalescing droplets, are liquid droplets that do not immediately coalesce with the bulk liquid; rather they remain floating on the surface for some amount of time before mixing. Such droplets have been studied in various liquids at ambient Earth temperature and pressures to improve industrial processes [1–3]. Because of Titan's low gravity (1.35 m/s^2), Titan's rain will have a low impact velocity (0.24–1.5 m/s [4]) compared to Earth (~10 m/s). This may result in the conditions necessary for the formation of such floating liquid droplets on the surface of Titan's liquid bodies after hydrocarbon rain events. No experimental studies, however, have investigated this phenomenon with liquid hydrocarbons in cryogenic conditions. This study aims to understand what occurs when a methane or ethane raindrop interacts with a methane-ethane-nitrogen liquid body on Titan's surface and investigates under what conditions will result in floating liquid droplets.

Methods: We conducted a set of experiments to simulate methane and ethane rain events under Titan surface conditions (89–94 K [5,6], 1.5-bar nitrogen atmosphere [7]), at the University of Arkansas' Titan Surface Simulation Chamber (Andromeda chamber; described in [8]). For ethane and methane rain events, liquid ethane and liquid methane are dripped from above into the bulk liquid below, respectively. During each "rain event" we record the composition and temperature of both the droplet and bulk liquid into which the droplets are falling. The methane–alkane composition is derived from the liquid mass and is expressed as the ratio, $f_{ratio}=X_{CH4}/(X_{CH4}+X_{C2H6})$ where X is in moles. When simulating ethane rain, the bulk liquid begins at 100 mol% methane-alkane ratio and decreases in methane concentration as ethane is introduced, while methane rain events begin with 100 mol% ethane (0 mol% methane–alkane ratio) and increases in methane concentration as methane is added.

Results: Ethane and methane floating liquid droplets are observed on bulk liquid compositions of 40–100 and 94–96 mol% methane-alkane ratio, respectively. These droplets have an initial diameter of 6 mm and remain on the liquid surface for a few seconds to a few minutes. Multiple ethane droplets also coalesce to form larger daughter droplets (Fig. 1). Our experiments have an impact velocity of 0.5–0.7 m/s, which is within range of the predicted impact velocity of a raindrop on Titan (0.24–1.5 m/s [4]). When investigating the influence of various liquid properties (surface tension, density, and viscosity [9]) on droplet formation, we find that surface tension and viscosity are the most influential liquid properties when forming floating liquid ethane and methane droplets, respectively.

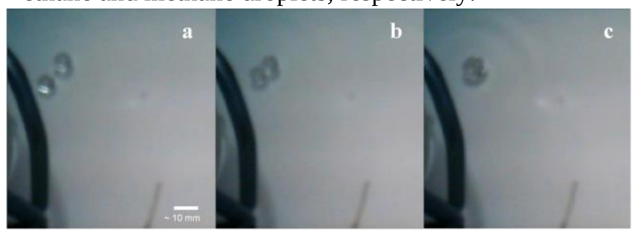

Figure 1*. Plan view of pure ethane liquid droplets floating on a 95 mol% methane–alkane ratio bulk liquid.* ***(a)*** *Two ethane droplets floating on the surface of the bulk liquid.* ***(b)*** *Two droplets are beginning to coalesce with each other.* ***(c)*** *Two droplets have coalesced to form a single larger daughter droplet.*

Conclusions: We conducted a set of experiments to simulate methane and ethane rain events under Titan surface conditions (89–94 K, 1.5-bar nitrogen atmosphere), and find that floating ethane droplets form on a wide range of lake/sea compositions, whereas methane droplets will only float on a narrow range of lake/sea compositions. We find the surface tenson of the droplet must be higher than the bulk liquid for ethane droplets to form, while the viscosity of the droplet cannot be higher than the bulk liquid for methane droplets to form. We propose that liquid droplets will form in Titan's methane-rich lakes and seas during ethane rain events with a droplet radius of ≤ 3 mm and an impact velocity of ≤ 0.7 m/s. Even though ethane is more dense than the bulk methane-ethane liquid, the presence of these droplets may result in an ethane-rich surface layer that does not initially mix with the liquid.

Acknowledgments: This work was funded by the NASA CDAP grant #NNX15AL48G. We thank W. Graupner Jr., E. Czaplinski, and K. Dzurilla for their support with the Titan Surface Simulation Chamber.

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Mapping the seasonal variability of gases from Titan's middle and upper atmosphere using ALMA

Emmanuel Garcia-Berrios[1,2] , Martin A. Cordiner[1,2] , Conor A. Nixon[1], Alexander E. Thelen[1,3], Steven B. Charnley[1]

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Introduction: We present a study of the impact of seasonal effects on the spatial distribution of Titan's atmospheric gases HNC, CH_3CN, and HC_3N over a timescale of less than a Titan month (9 Earth months). These molecules are synthesized primarily in the upper and middle atmosphere as a result of CH_4 and N_2 photochemistry, and are redistributed around Titan's globe as a result of diffusion and zonal and meridional circulation. With observations from the Atacama Large Millimeter/submillimeter Array (ALMA) obtained in August 2016 [1] and May 2017 [2], we produced high-resolution, spectrally and spatially resolved maps of the emission from these gases. These observations are contemporaneous with the end of the Cassini mission (around the time of the northern summer solstice), allowing for studies of seasonal variations in Titan's organic chemistry through analysis of the production, destruction, and transport of complex molecules. Over the north pole, we observed a strong reduction of 41% ± 4% in HC_3N flux, while CH_3CN remained relatively stable (within errors) over the 9 month period of our observations. At the south pole, CH_3CN presented a 31% ± 10% increase, and HC_3N remained fairly stable (within errors). The HNC emission comes primarily from the highest (thermospheric) altitudes, and is distributed more uniformly about Titan's limb than HC_3N and CH_3CN; the latter two molecules show strong polar enhancements due to meridional circulation. The steep decline in the HC_3N north polar concentration is consistent with its short photochemical lifetime (compared to CH_3CN), combined with a reduction in meridional transport of gases produced at lower latitudes, towards the northern (summer) pole. The loss of emission of HC_3N in the northern hemisphere is also consistent with the breakdown of Titan's northern polar vortex during the onset of the northern summer, leading to a loss of confinement of this species [3].

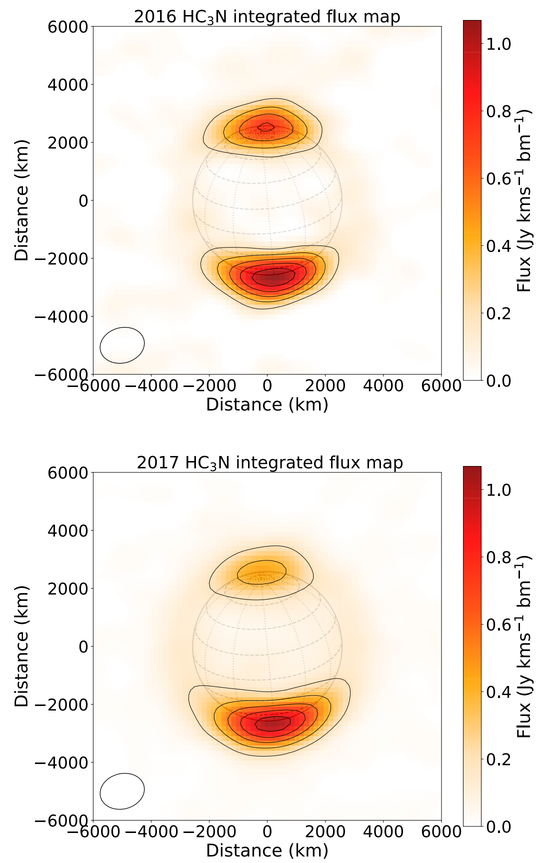

Figure 1: Integrated emission maps for HC_3N observed with ALMA in August 2016 (top) and May 2017 (bottom). Contours are in intervals of 7σ. The wireframe represents Titan's surface and orientation. The ellipse in the lower left shows the spatial resolution (0.23"x 0.18").

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THE EFFECTS OF PROPANE ON THE LIQUIDS OF TITAN. J. Hanley[1,2], B. Wing[3,2], A.E. Engle[2,1], G.E. Lindberg[2], W.M. Grundy[1,2], S. Dustrud[2], S. Tan[4], S.C. Tegler[2]. [1]Lowell Observatory, Flagstaff, AZ (jhanley@lowell.edu), [2]Northern Arizona University, Flagstaff, AZ, [3]Arizona State University, Tempe, AZ, [4]Planetary Science Institute, Tucson, AZ.

Introduction: The lakes and seas of Titan are composed primarily of methane (CH_4) and ethane (C_2H_6), with the concentration of dissolved nitrogen (N_2) depending on the ratio of methane to ethane, the temperature, and pressure. Propane (C_3H_8) is formed photochemically in the upper atmosphere of Titan, and condenses at the tropopause. The freezing point of pure propane is 85.5 K, meaning that it would be liquid on the surface of Titan, like methane and ethane. We have begun an exploration of the effect of propane on methane, ethane, nitrogen, and their mixtures.

Experimental: Northern Arizona University (NAU) hosts the Astrophysical Materials Laboratory [1, 2]. Cryogenic samples are studied via Raman spectroscopy and photography. Our observations of propane mixtures revealed some behaviors that diverge from the behavior of pure propane. The 51% propane-49% ethane mixture froze at 74.9±0.5 K while the ideal eutectic calculation indicated this should occur at 75.5 K. Meanwhile, the 32% propane-68% methane mixture froze at 79.0±0.5 K, compared to the 69.4 K predicted by the ideal eutectic calculation [1].

As nitrogen was added to a binary hydrocarbon mixture, it caused the formation of a second liquid (Figure). The droplets form at the meniscus and this nitrogen-rich denser liquid falls once enough material has collected to break surface tension. The difference in behavior of the propane-ethane system and the propane-methane system can be attributed to the difference in nitrogen solubility. For further analysis, the phase diagrams at conditions where the second liquids were observed were calculated using CRYOCHEM [3].

Numerical Simulations: We examined a homogeneous N_2:CH_4:C_2H_6:C_3H_8 liquid system to understand the breakdown of ideality. In these simulations, real effects are quantified by calculating the binding free energy between each pair of molecules. We found that the binding free energies of N_2 to CH_4, C_2H_6, and C_3H_8 are -0.86, -0.60, and -0.35 kJ/mol, respectively. This is typically compared with the thermal energy k_BT, which is 0.83 kJ/mol at 100 K, to estimate the 'stickiness' of two molecules. When the magnitude of the thermal energy is greater than the binding free energy, the molecules have the kinetic energy to separate. This reveals that increasing alkane length results in a decrease in binding strength between N_2 and each of the alkanes, which suggests a molecular explanation for the phase behavior observed in the experiments of these systems at lower temperatures.

Implications and Future Work: Pure propane should not freeze on the surface of Titan. However, we see propane ice form under certain conditions that might be possible on Titan (Fig left). We also see that the liquid-liquid system can form with the addition of propane. We continue to explore the effects of propane on methane, ethane and nitrogen, both individually and additively, and constrain the conditions under which interesting phenomena occur.

Acknowledgments: This work was sponsored in part by NASA SSW grant #80NSSC18K0203 and NSF REU grant #1461200.

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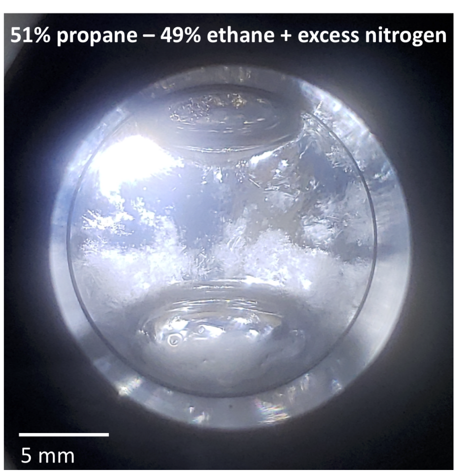

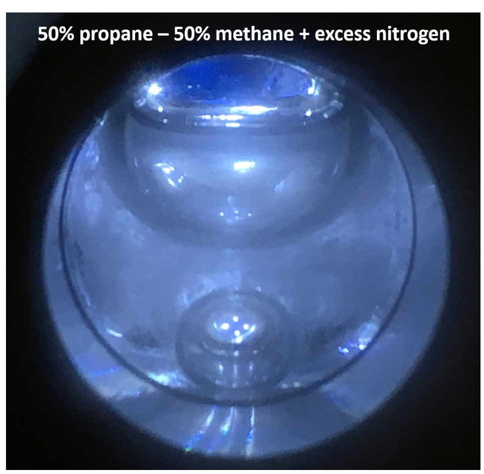

Left: Image of propane-ethane mixture with excess nitrogen (74.9 K), showing two liquid phases. Right: Image of propane-methane mixture with excess nitrogen (79 K), showing two liquid phases. The top liquid collects and drips through the middle liquid layer, and collects at the bottom.

Simulating the seasonal evolution of polar stratospheric ice cloud. L. E. Hanson[1], D. W. Waugh[1], E. L. Barth[2], C. M. Anderson[3], [1]Department of Earth & Planetary Sciences, Johns Hopkins University, Baltimore, MD 21218, [2]Southwest Research Institute, Boulder, Colorado 80302, [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771.

Introduction: Both Voyager I and Cassini observed thick seasonal stratospheric clouds in Titan's polar regions, but there are many unanswered questions regarding their formation mechanisms, composition, and evolution [1]. One of these clouds consisting of HCN condensate was first observed in 2012, mid southern fall, at an altitude of 300 km near the south pole [1–3]. The appearance of condensed HCN at 300 km was surprising, as it implies extremely rapid cooling of the polar stratopause in order to reach the HCN frost point [2]. Rapid cooling near the south pole mesopause is observed, however the formation and evolution of condensates in this region has not been studied using cloud microphysical modeling, and it is unknown if polar temperatures can explain the observed cloud.

In order to better understand the formation and evolution of HCN cloud in Titan's polar regions, we perform simulations using the Titan version of the Planet Community Aerosol and Radiation Model for Atmospheres (PlanetCARMA) [4]. PlanetCARMA is a flexible atmospheric column model that can simulate complex microphysics involving multiple species, though for this work we simulate pure HCN ice with an aerosol representing Titan's refractory haze. Although it is a trace atmospheric constituent, HCN cloud has been frequently observed across Titan [1].

Results: Cassini observations cover slightly less than half of a full Titan year, but assuming the seasonal temperature profile evolution is similar at both poles we approximate the annual temperature evolution by combining winter and spring profiles from the north with summer and fall profiles from the south. We use temperature profiles interpolated from CIRS observations by [5] to estimate the annual temperature evolution for a "model" polar stratosphere. Because the greatest temperature variability occurs during the fall, we use an adjusted solar longitude, L_s, defined so that $L_s = 0°$ at the fall equinox. With the onset of southern fall, the upper stratosphere cools rapidly, reaching a minimum temperature at about $L_s = 60°$. Cooling in the lower stratosphere appears to continue until the start of winter, though we have no data from early winter at either pole (see Fig 1a).

The cloud top altitude of the simulated HCN cloud using these temperatures are shown in Fig 1b, for two different vapor pressure functions ([6] provide the most reliable parameterization for equilibrium vapor pressure of HCN ice, but we also run simulations using [7] to test the sensitivity). Modeled cloud top altitudes peak at $L_s = 60°$ or 85°, depending on the vapor pressure parameterization, after which the cloud top gradually descends throughout the remainder of the year. The large difference in cloud top altitude between the two vapor functions is due to the steep lapse rate in the observed temperature profile.

In order to test the sensitivity of these results to vapor abundance, we re-run the $L_s = 60°$ simulation with the vapor flux at the top of the model, f_v multiplied by 10, 100, 1000 (see Fig 1b), which increases the HCN mixing ratio at 300 km from 1.7×10^{-6} to 1.4×10^{-5}, 1.2×10^{-4}, and 9.2×10^{-4}, respectively. This results in an increase in cloud top altitude, and less sensitivity to the vapor pressure function. However, none of these simulations produce cloud at 300 km.

Additional sensitivity simulations are being performed, including simulations using modified temperatures. The temperature profiles are interpolated from observations at lower latitudes due to gaps in the available measurements, so actual polar conditions may be significantly colder. These simulations help to address measurement gaps by constraining the conditions necessary to produce observed clouds. In addition to cloud top altitude, model output may be validated by comparing with retrievals of vapor mixing ratio profiles.

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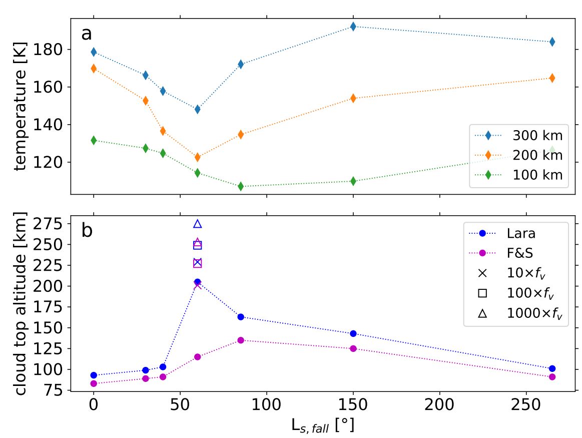

Fig 1. Upper: temperatures at select altitudes. Lower: modeled cloud top altitude.

HEAVY POSITIVE ION GROUPS IN TITAN'S IONOSPHERE: CASSINI PLASMA SPECTROMETER IBS OBSERVATIONS.

R. P. Haythornthwaite[1,2], A. J. Coates[1,2], G. H. Jones[1,2], A. Wellbrock[1,2], J. H. Waite[3], V. Vuitton[4] and P. Lavvas[5],
[1]Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Dorking, UK, [2]The Centre for Planetary Sciences at UCL/Birkbeck, London, UK, [3]Space Science and Engineering Division, Southwest Research Institute, San Antonio, Texas, 78228, USA, [4]Institut de Planétologie et d'Astrophysique de Grenoble, Univ. Grenoble Alpes, CNRS, Grenoble 38000, France, [5]Université de Reims Champagne Ardenne, CNRS, GSMA UMR 7331, 51097 Reims, France

Introduction: Titan's ionosphere contains a plethora of hydrocarbons and nitrile cations and anions as measured by the Ion Neutral Mass Spectrometer and Cassini Plasma Spectrometer (CAPS) onboard the Cassini spacecraft[1].

Previous ion composition studies in Titan's ionosphere by Cassini instruments revealed "families" of ions around particular mass values and a regular spacing of 12 to 14 u/q between mass groups[2]. These are thought to be related to a carbon or nitrogen backbone that dominates the ion chemistry[2]. Previous studies also identified possible heavy ions such as naphthalene, anthracene derivatives and an anthracene dimer at 130, 170 and 335 u/q respectively[1].

Methodology

The CAPS Ion Beam Spectrometer[3] is an electrostatic analyser that measures energy/charge ratios of ions. During the Titan flybys Cassini had a high velocity (~6 km/s) relative to the low ion velocities (< 230 m/s) observed in the ionosphere. The ions were also cold, having ion temperatures around 150K. These factors meant that the ions appeared as a supersonic beam in the spacecraft frame and that their measured energies appear at kinetic energies associated with the spacecraft velocity and the ion mass, therefore the measured energy/charge spectra can be converted to mass/charge spectra.

Results and Conclusions

Positive ion masses between 170 and 310 u/q are examined with ion mass groups identified between 170 and 275 u/q containing between 14 and 21 heavy (carbon/nitrogen/oxygen) atoms[5]. These groups are the heaviest positive ion groups reported so far from the available *in situ* ion data at Titan.

The ion group peaks are found to be consistent with masses associated with Polycyclic Aromatic Compounds, including Polycyclic Aromatic Hydrocarbon (PAH) and nitrogen-bearing polycyclic aromatic molecular ions. The ion group peak identifications are compared with previously proposed neutral PAHs[6] and are found to be at similar masses, supporting a PAH interpretation. The spacing between the ion group peaks is also investigated, finding a spacing of 12 or 13 u/q indicating the addition of C or CH.

The discovery of these groups will aid future atmospheric chemical models of Titan through identification of prominent heavy positive ions and further the understanding between the low mass ions and the high mass negative ions, as well as the process of aerosol formation in Titan's atmosphere.

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SIMULATIONS FOR TIME-RESOLVED NUCLEAR SPECTROSCOPY ON TITAN. L. E. Heffern[1], C. J. Hardgrove[1] [1]*Arizona State University (School of Earth and Space Exploration, Tempe, AZ Lheffern@asu.edu)*

Introduction: Gamma-ray and neutron spectrometers (GRNS) can be used to determine the elemental abundances and hydrogen content within the top ~tens of centimeters of planetary surfaces. The first planetary active neutron investigation, the Dynamic Albedo of Neutrons on the Mars Science Laboratory (MSL), is returning significant scientific results from the surface of Mars [1, 2]; the recently selected Dragonfly mission to Saturn's Titan will also carry an active GRNS instrument (DraGNS) [3].

Background: Titan's atmospheric density (0.00539 g/cc) & composition are both well-known from the Huygens probe [4, 5]. The atmosphere on Titan is dominated by N with small amounts of H and C, which tend to condense in the atmosphere, creating tholin hydrocarbons which can later rain down to the surface [5]. We inferred our base composition of Titan's surface material to be a dune-like mixture of methane water-ice ($4CH_4{\cdot}23H_2O$), ammonia water-ice ($xN_3H{\cdot}XH_2O$), and tholin hydrocarbons (e.g. C_6H_6 & C_3HN) based on hypotheses from various studies of Huygens probe data [5-9].

Simulation studies: We used the Monte Carlo N-Particle 6.1 simulation tool from Los Alamos National labs to simulate scenarios, with studies grouped into three levels. *Level-0 simulations* consist of a simple "bubble world" with dune material & atmosphere material, a DT-neutron point source positioned 50 cm above the dune surface, & particle tally surface placed at 50 cm in line with the source. *Level-1 simulations* consist of the bubble world with interchangeable GRNS instruments added (^{3}He, HPGe, LaBr, CLYC), along with PNG materials. *Level-2 simulations* include everything from *level-1* along with a mock rover model & MMRTG power source, assumed to be similar to the one used on MSL.

For initial studies of Titan, we used level-0 simulations to study the effects of atmospheric density on the neutron environment. For this study we modeled a fully atmospheric Titan world & a ½ atmospheric, ½ dune world to observe effects on the total neutron spectrum. **Figure 1** shows the differences in the neutron environment between Titan materials resulting from our studies and other planetary surfaces. We performed studies to explore the limits and utility of neutron die-away techniques with a pulsed neutron generator on Titan, using level-0 simulations for mixed materials & layered materials (e.g. high-N deposits, biosignatures, tholins), **Figure 2.**

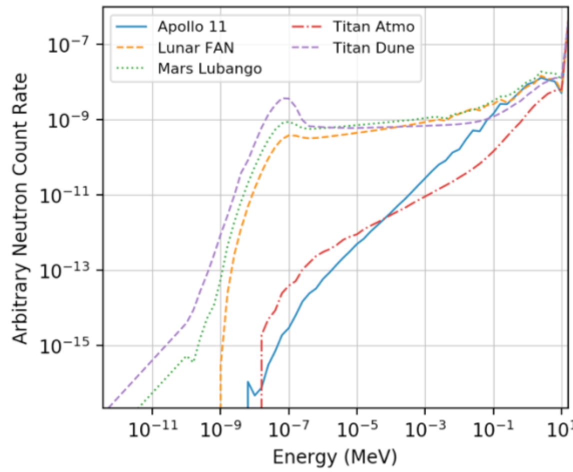

Figure 1: Simulated neutron environment spectra using a DT generator on planetary surfaces.

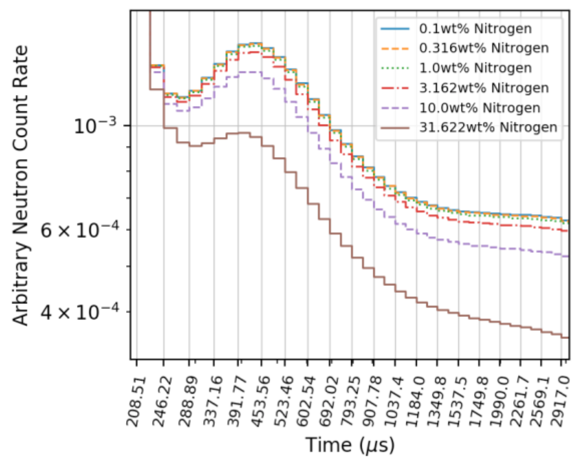

Figure 2: Single layer model of Titan dune material with increasing amounts of N distributed throughout the dune material.

References: [1] S. Czarnecki, et al. JGR: Planets, 125, 2020; [2] Gabriel, T. S. J., et al. JGR: Letters, 45, 12,766–12,775, 2018; [3] Parsons, A., et al. NIM:A, Vol 652(1), 2011, pp. 674-679; [4] Fulchignoni, M., and Et al. Nature, vol. 438, no. 7069, 2005; [5] Niemann, H. B., et al. Nature, vol. 438, no. 7069, 2005, pp. 779–784; [6] Cable M. et al. Chem. Rev., 112, 2012, pp. 1882-1909; [7] McCord, Thomas B., et al. Icarus, vol. 194, no. 1, 2008, pp. 212–242; [8] Aharonson, et al. (Cambridge Planetary Science, pp. 63-101). Cambridge: Cambridge University Press, 2014; [9] Lorenz, Ralph D. IAU, vol. 4, no. S251, 2008.

SIMULATIONS FOR TIME-RESOLVED NUCLEAR SPECTROSCOPY ON TITAN.

L. E. Heffern[1], C. J. Hardgrove[1] [1]*Arizona State University (School of Earth and Space Exploration, Tempe, AZ Lheffern@asu.edu)*

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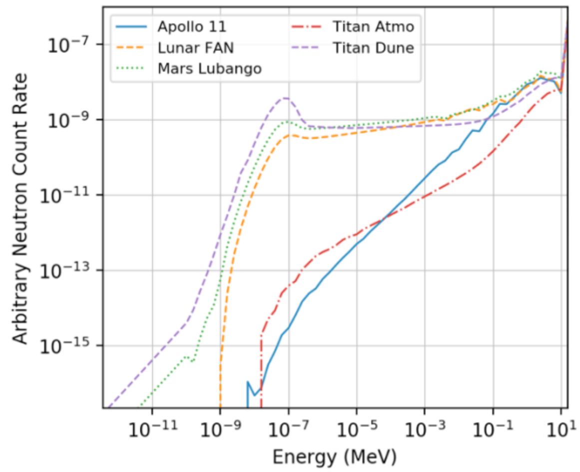

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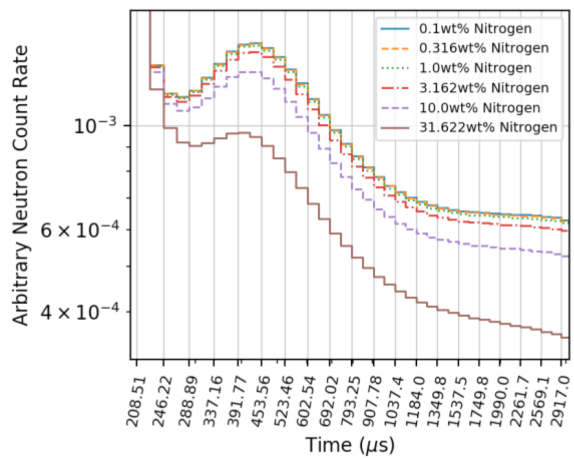

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PHYSICAL OCEANOGRAPHY IN THE COASTAL ZONES OF TITAN'S PUNGA MARE. M.F. Heslar[1] and J.W. Barnes[1], [1]Department of Physics, University of Idaho (hesl6778@vandals.uidaho.edu)

Introduction: Oceanographic activity, such as ocean currents and surface waves, has been explored by RADAR "magic islands" on Ligeia Mare [1, 2] and near-infrared VIMS observations of specular glint and sun glitter on Kraken Mare [3]. However, surface activity on Punga Mare remains unexplored, except a single detection of probable capillary wind waves [4]. The lake environment should not limit the diversity of air-sea-land interactions compared to the larger Maria. Also, Punga Mare hosts a diversity of coastlines, like Ligeia Mare [5], that suggests coastal erosion.

Specular glint observed on sea surfaces from orbit reveal details of oceanographic activity on Earth [6] and Titan [3, 4] alike. We interpret a high-sampling Cassini VIMS observation, CM_1805211625_1, of specular glint over eastern Punga Mare from the T110 flyby. In Figure 1, the T110 observation shows a plethora of anomalous sea surface features, which suggests surface interactions on the Punga coasts.

The high phase (126°) of this observation causes a bright mirror-like reflection of the sky on Punga Mare. The specular point is located off the right side of the unprojected image in Figure 1. There are typically two concentric zones in a specular glint observation: the specular and sun glitter zones [4, 6]. In the specular zone, smooth (rough) sea surfaces appear brighter (dark) than the background sea surface. The opposite holds true for the sun glitter zone. We assume the zone transition occurs at 2.25°, based on prior interpretations of specular VIMS observations [3].

Discussion: We will discuss the possible physical interpretations of the anomalous features cited in Figure 1. First, the channeled terrain of Ipyr Labyrinthus has been noted as a 5-µm-bright, organic-rich feature in many VIMS observations [7]. Second, we note a line of brightened pixels near Apanohuaya that likely indicates liquid fill. Third, we note a set of brightened pixels aligned with the seaside of RADAR coastlines. Fourth, the eastern Fundy Sinus sea surfaces host variegated brightness, likely caused by variable sea states. Fifth, sun glitter appears near an archipelago (Hawaiki Insulae) that may suggest a direct interplay between surface winds and topography. Finally, we note several bright pixels at the backside of Punga bays (Sinus) that may correspond with river debouches (runoff from a small channel emerging into a broader liquid body).

Overall, the anomalous surface features depict the dynamic nature of the lake environments and an active hydrological cycle on Titan.

References: [1] Hofgartner et al. 2014 [2] Hofgartner et al. 2016 [3] Heslar et al. 2020 [4] Barnes et al. 2014 [5] Wasiak et al. 2013 [6] Strong & Ruff 1970 [7] MacKenzie & Barnes 2016

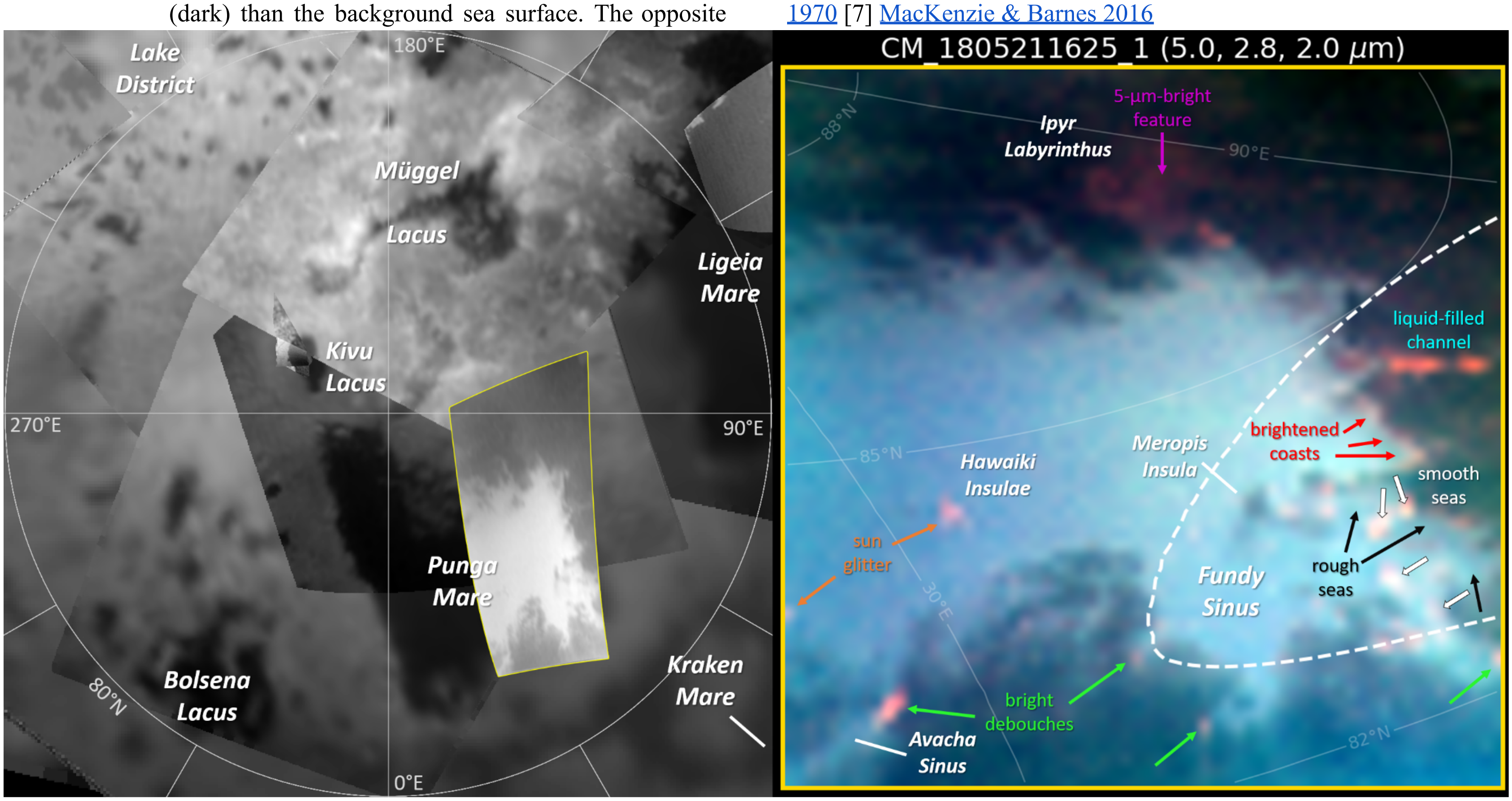

Figure 1: *T110 observation of infrared specular glint on Punga Mare* | **Left:** 2.03 µm polar stereographic mosaic of Titan's north polar region above 80°N from Cassini VIMS observations corrected for airmass and resolution. A yellow outline denotes the footprint of T110 VIMS observation. The high phase angle (126°) inverts the surface brightness such that liquid surfaces are brighter than the rougher land. **Right:** Unprojected color composite (RGB: 5.0, 2.8, 2.0 µm) of the same T110 VIMS observation with a superimposed geographic grid and IAU-approved feature names. Anomalous sea surface features of interest are pink and purple. The white dashed line indicates the transition between the specular and sun glitter zones.

PAST POLAR ICE CAP GLACIATION ON TITAN. Elainie Huncik[1] and Pascal Lee[2,3,4], [1]Department of Physics, Astronomy, Geology, & Environmental Sciences, Youngstown State University, 1 University Plaza, Youngstown, OH 44555, USA, echuncik@student.ysu.edu, [2]SETI Institute, [3]Mars Institute, [4]NASA Ames Research Center.

Introduction: Titan's polar regions present vast areas of clustered, round, irregular depressions several to tens of kilometers across, with hectometer-scale raised rims and steep perimeters, some dry with flat floors, others containing liquid [1,2] **(Fig.1)**. The dry depressions appear to be lake basins while the liquid-filled ones are hydrocarbon lakes [1]. Several hypotheses have been proposed for the origin of these depressions, each with unresolved issues: *impact craters* [4], *karst* [5-10], *thermokarst* [11,13], *cryovolcanism* [12,13]. A common puzzle is the concentration of the depressions in Titan's polar regions.

Landscape of Deglaciation on Titan: Several combined morphologic characteristics of Titan's north polar depressions, esp. their raised rims, roughly circular outline, tight size distribution, depths of up to hundreds of meters, clustered and nested yet disorganized spatial distribution, and their rough (radar bright) surroundings, are characteristic of the fields of depressions on Earth associated with deglaciation known as *kettle holes* when dry, and *kettle* lakes when filled with meltwater. Kettle holes/lakes on Earth form when blocks of ice left by retreating or disintegrating glaciers, ice caps, or ice sheets, sink into their soft substrate, melt, and eventually leave a deep hole. The largest kettle holes/lakes on Earth are multi-km long and over 100 m deep. While kettle holes/lakes and thermokarst depressions/lakes are both found in once ice-rich settings, the former are fundamentally depositional landforms and can present substantial relief, whereas the latter are erosional landforms of shallow depth.

Titan's polar depressions produce landscapes consistent with deglaciation following the disintegration and departure of past regional ice covers. The concentration of the depressions at high latitudes suggests polar ice caps, dominated by either methane, acetylene, ethane, nitrogen, or mixtures thereof, depending on past glacial climate regimes. The proposed polar glaciations might have waxed and waned with Titan's phases of climate warming and cooling [14,15].

Other Candidate Glacial Features: U-shaped valleys, fjords, morainal arcs, and arêtes, are among glacial features previously interpreted on Titan [10,11,16]. In addition to the interpretation of polar depressions as possible kettle holes/lakes, we report identifying sinuous ridges several kilometers in length meandering between the depressions, which we interpret as possible *eskers*, and valley networks previously interpreted as fluvial features [3], which we interpret instead as possible subglacial or ice-marginal melt fluid channels on the basis of morphologic analogs from Devon Island in the High Arctic [17] **(Fig. 2).**

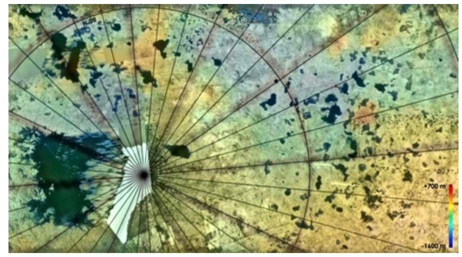

Figure 1: *Titan North polar radar reflectivity and topography. (Cassini Radar / NASA JPL / Topography from [18]).*

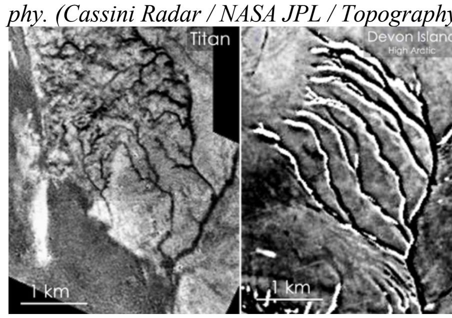

Figure 2: *L: Valley networks on Titan (Cassini RADAR / NASA JPL) vs R: Subglacial & ice-marginal meltwater channel networks, Devon Island, Arctic (GSC / NASA HMP).*

Discussion: In this study, we propose that past polar ice cap glaciation(s) and subsequent deglaciation likely produced several major categories of surface features on Titan, in particular its polar depressions and lakes, sinuous ridges, and valley networks. The latter might still be active as surface runoff at present, their origin is interpreted here as resulting from subglacial or ice-marginal melting. Current radar spatial resolutions don't allow decisive testing of origin hypotheses for Titan's polar depressions. Future directions of work include exploring climate models for polar glaciations, predictions of isostatic depression and rebound in soft crustal materials, and when *Dragonfly* reaches Titan, higher resolution surface imaging.

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DUST DEVILS ON TITAN. B. Jackson[1] (bjackson@boisestate.edu), Jason W. Barnes[2], & Chelle Szurgot[1]. [1]Dept of Physics, Boise State University, 1910 University Drive, Boise ID, [2]Dept of Physics, University of Idaho, Moscow ID

Introduction: Conditions on Saturn's moon Titan suggest dust devils, convective, dust-laden plumes, may be active. Although the exact nature of dust on Titan is unclear, previous observations confirm an active aeolian cycle [1], and dust devils may play an important role in Titan's aeolian cycle, possibly contributing to regional transport of dust and even production of sand grains. The Dragonfly mission will document dust devil and convective vortex activity and thereby provide a new window into these features. Our analysis shows that associated winds are likely to be modest and pose no hazard to the mission. Instead, probing of the dust devils' pressure and wind profiles will enable novel experiments in aeolian processes on the surface of Titan, allowing us to explore the thresholds for dust and sand transport. The results presented here are published in [2].

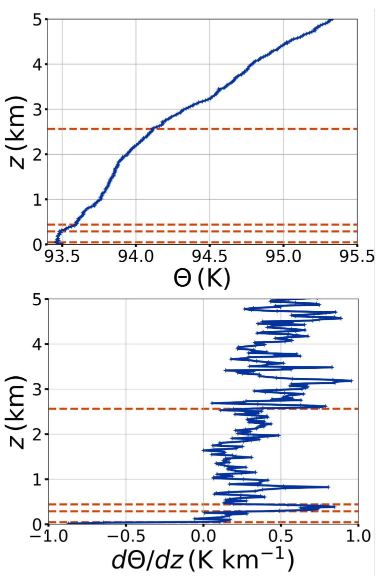

Fig. 1. Titan's potential temperature profile and its derivative. The top panel shows the inferred potential temperature profile (blue), while the bottom panel shows the smoothed derivative. The dashed orange lines indicate statistically significant kinks in the profile.

Titan's Boundary Layer: Titan's meteorological conditions determine convective vortex and dust devil occurrence and properties (wind speeds, sizes, occurrence frequency, etc.). The structure of the planetary boundary layer plays a key role and was probed at high resolution by the Huygens probe [3]. Figure 1 shows the potential temperature profile θ derived from these measurements [4]. We searched for statistically robust change points in the profile's derivative, which may correspond to boundary layer depth h. Frequent convective overturn takes place in the boundary layer, which can produce a region of uniform potential temperature. Thus, a change in the potential temperature profile may reflect the top of the planetary boundary layer, as suggested by previous studies [4].

Titan's Dust Devils: Dust devils can be modeled as Carnot heat engines [5] with a thermodynamic efficiency that depends on the atmospheric temperature and pressure structure, as well as the boundary layer depth h. Based on [5], we can estimate the pressure deficit in a dust devil ΔP. Cyclostrophic balance in a convective vortex gives the tangential wind speed at the eyewall as $\upsilon \approx \Delta P/\rho$, where ρ is the atmospheric density. Figure 2 shows the expected values for a range of temperature perturbations ΔT. The expected thresholds for lifting Titan dust with various diameters D_p are shown as well.

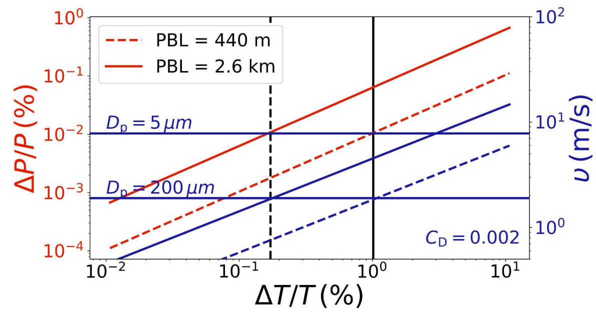

Fig. 2. The pressure perturbations (orange curves) and tangential wind velocities (blue curves) for a given temperature perturbation. The dashed lines assume a planetary boundary layer (PBL) 440 m deep, and the solid lines for a depth 2.6 km. The solid, horizontal blue lines show the threshold wind speeds to initiate particle movement with diameters Dp = 5 um (dust) and 200 um (sand).

With wind speeds of a few m/s, any convective vortex would only moderately perturb Dragonfly's flight, and so dust devils (or dustless convective vortices) likely pose no threat to Dragonfly. (See also [6].) However, assuming dust devils reach Dragonfly's flight altitude (~500 m), scaling laws based on terrestrial and martian dust devils [2] suggest Dragonfly might encounter two or three dust devils during each flight (assuming they are active in Titan's early morning) and one every 3.6 Earth hours while landed, nearly 20 devils each Titan day.

Field studies with instrumented drones have helped reveal interior structures within terrestrial dust devils and may provide key evidence to unravel the still-obscure mechanisms by which devils loft dust [2]. Likewise, Dragonfly's imagery and meteorological data may break new ground by showing how they operate in a novel aerodynamic environment.

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The thermodynamics of Titan's abysses, Part I:
Equation of State of water-ammonia solutions at conditions of Titan's hydrosphere

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Introduction: Titan's water-rich hydrosphere is believed to host a deep liquid ocean below the icy surface, and possibly a layer of high pressure ices [1]. The composition of the hydrosphere remains cryptic, but it is likely that ammonia, and salts such as NaCl, are the main solutes [2]. The structure, geodynamics and astrobiological potential of Titan's deep ocean depend on how these solutes affect i) the thermodynamic properties of the ocean and ii) the associated phase stabilities of fluids and solids.

Unfortunately very few data exist pertaining to the thermodynamic behavior of H_2O-NH_3 mixtures at high pressures, and none for H_2O-NH_3-NaCl. It is therefore necessary for our understanding of Titan, and for future exploration using geophysical techniques (e.g. the seismic package on NASA's DragonFly mission), to have an accurate and internally self-consistent equation of state of aqueous solutions containing ammonia and salts.

Results: We present a new equation of state (EoS) for water-ammonia solutions based on recently obtained sound speed and melting line measurements, made at high pressures and low temperatures. The new EoS, which uses the local basis function framework, is valid across the entire range of conditions expected in Titan's ocean, from 200 to 400K, and up to 800 MPa. Coupled with the EoS of ice polymorphs (contained in the SeaFreeze package [3]) the new formulation accurately reproduces the phase stability of these solids at high and low pressures.

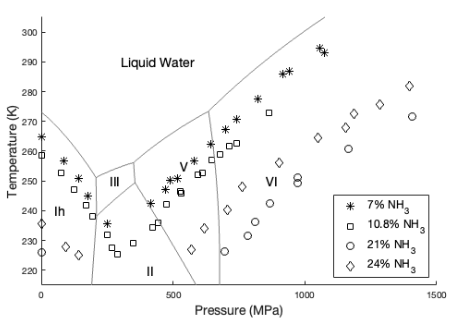

Figure 1: New measurements of ice polymorphs melting point depression (ice Ih and VI).

Sound speed measurements on H_2O-NH_3 solutions were made with an ultrasonic, high-pressure, low-temperature apparatus at UW. Data were obtained for solutions with up to 30% concentration of dissolved NH_3, in the ranges 253-353K and 0.1-700 MPa. We also obtained new liquidus measurements of ice polymorphs (Ih, VI and VII) down to 225K and up to 2000 MPa, using a high pressure, diamond anvil cell, coupled with a ruby pressure gauge and a thermoelectrically cooled cryostat (Figure 1).

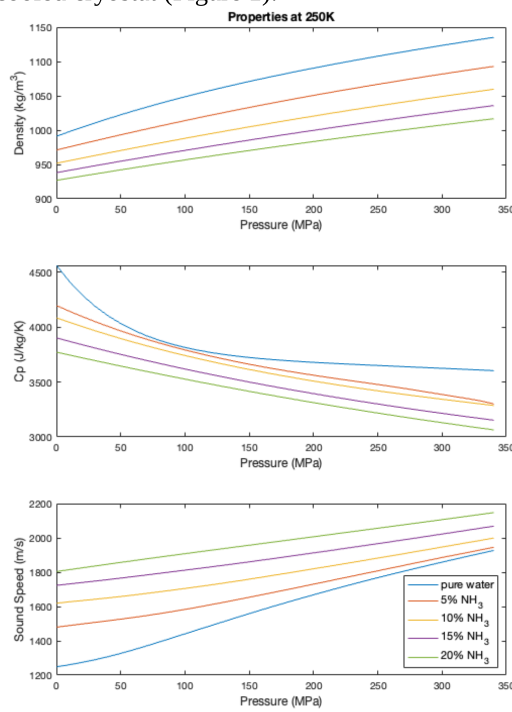

Figure 2: Example thermodynamic properties (density, Cp and sound speed) for H_2O-NH_3 solutions at 250K up to 350 MPa and 20 mol% from the new equation of state.

We will report aspects of the EoS (Figure 2) and discuss their implications for modeling the interior of Titan. (A separate presentation by Vance et al. in this workshop will report the first application to the structure of Titan.) We will finally consider upcoming results on the combined effects of aqueous NH_3 and NaCl, which will allow a more detailed study of realistic variations in oceanic chemistries, on the structure, dynamics, habitability and exploration of the interior of Titan.

Acknowledgments: The present research was supported by the Titan nodes of NASA's Astrobiology Institute (17-NAI8-2-017).

References: [1] Journaux et al. (2020) *Space Sci. Rev* **217**, 7. [2] Vance et al. (2018) JGR Planets **123**, 1. [3] Journaux et al. (2020) JGR Planets **125**, 1.

PROFILING TITAN'S HAZY ATMOSPHERIC LIMB WITH *CASSINI* VIMS. S.M. Kreyche[1], M.F. Heslar[1], J.W. Barnes[1], W.J. Miller[1], S.M. MacKenzie[2], [1]Department of Physics, University of Idaho, [2]Johns Hopkins University Applied Physics Laboratory. (stevenkreyche@gmail.com)

Introduction: The vertical structure and properties of Titan's extended hazy atmosphere evolved throughout the duration of *Cassini's* stay in the Saturn system [1]. Our understanding of these phenomena remains limited. Although the data gathered by the *Huygens* probe was instrumental in constraining the lower atmosphere's scattering phase functions, it only sampled Titan's equatorial region and was not equipped to see wavelengths longer than 1.6 μm [2]. Additional opportunities to study Titan's atmosphere include solar occultation observations and close approaches of Titan by *Cassini*.

Methods: Limb cubes from *Cassini* Visual and Infrared Mapping Spectrometer (VIMS) at high spatial sampling are a previously unexploited resource that we use to gain insight into Titan's hazy lower atmosphere (stratosphere and troposphere). We use VIMS cubes within a spacecraft distance of 55,000 km or spatial sampling of 25 km/pixel to extract high-quality I/F (brightness) profiles.

Figure 1 shows an example VIMS cube and limb profile. We note that surface contamination occurs in the two bottommost altitude bins, inverting the I/F limb profile at 0-50 km.

Preliminary Analysis: We conducted a study of the evolution of Titan's equatorial (45°S-45°N) limb profiles over time and phase angle. We isolated the equatorial atmosphere as it does not exhibit complex seasonal cloud patterns (e.g. polar hood [3]). We developed an initial database of 98 VIMS limb cubes at NIR wavelengths across the entire *Cassini* mission (2004-2017). In addition, we investigated the evolution of atmospheric spectral features at different altitudes.

Conclusions & Future Work: We have a sufficient VIMS limb profile database to study the evolution of the lower atmosphere. In order to simulate the vertical structure of Titan's atmospheric haze, we will employ SRTC++, a 3D spherical radiative transfer model that can handle tangential limb observation geometries, including those near the terminator [4]. We will use SRTC++ to fit the observed limb profiles, which will enable us to infer the structure and properties as a function of phase angle and time. Future investigations will include simulating the evolution of the VIMS limb brightness across the terminator, which is poorly understood [5].

References: [1] Seignovert et al. 2021 [2] Tomasko et al. 2008 [3] Lorenz et al. 2006 [4] Barnes et al. 2018 [5] Muñoz & West, 2018

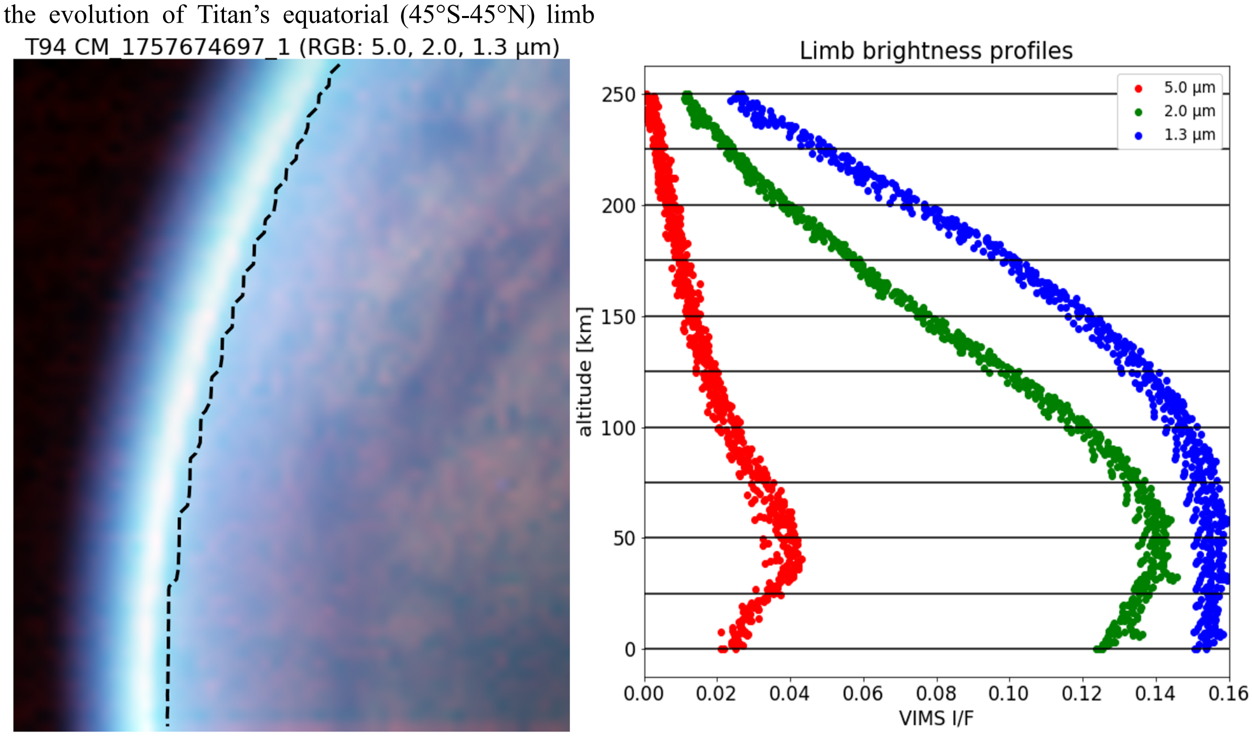

Figure 1: *Left:* A T94 VIMS near-infrared (NIR) limb image. The dashed line indicates the atmosphere-surface boundary. *Right:* Atmospheric limb profiles at NIR wavelengths of the RGB image. Black lines are altitude bins.

THE ROLE OF SEASONAL SEDIMENT TRANSPORT AND SINTERING IN SHAPING TITAN'S LANDSCAPES.

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Introduction: Alongside Earth and Mars, Titan is the third planetary body in the solar system to show evidence for widespread and diverse sedimentary environments, including lakes, rivers, alluvial fans or deltas, eroded canyonlands, dissected plateaux, and sand dunes. The latitudinal distribution of Titan's terrains, with sand dunes largely concentrated around the moon's equatorial belt, undifferentiated plains at mid-latitudes, and labyrinth terrains and lakes near the poles [1], suggests a strong control of climate on Titan's surface processes and landscape formation. Climate models predict that intense mid-latitude and equatorial storms may drive significant sediment transport by winds and rivers [2]. In addition to models, thirteen years of episodic Titan flybys by *Cassini* revealed that the moon's methane cycle includes methane rainstorms and even inundation [3], with more storms near the poles than near the equator. Furthermore, the morphology and crestline orientations of Titan's equatorial dunes suggest that they have been active over the recent past (10s–100s kyrs, or ~3,000–45,000 Titan years) [4], and ongoing dune formation is further supported by the presence of compositionally distinct interdune areas [5–6]. Thus, models and spacecraft observations indicate that seasonal, active sediment transport shapes the modern landscapes of Titan.

From saltation mechanics, we know that grain sizes within the dune field should be narrowly distributed, and on Titan, are predicted to be around 200–300 μm in diameter [e.g., 7] (although coarser grains are permitted if dune materials are cohesive [8]). Several mechanisms have been proposed to generate sand on Titan, such as the erosion of lithified materials in the mid-latitudes, sintering of photochemical airfall particles, flocculation, and evaporitic precipitation [9]. Laboratory experiments suggest that the organic materials thought to make up dune sands [e.g., 5, 10–11] are mechanically weak [12], such that dune sand could be highly susceptible to comminution (fining through abrasion) during transport on Titan – an apparent paradox that has led to the hypothesis that Titan's dune sand is likely derived locally [12]. Here, we first explore the hypothesis that Titan's dune sand is fining through time due to progressive abrasion, but that the dunes have been able to persist over 10s–100s kyrs without local sand replenishment because aeolian abrasion is slow. Then, we explore the hypothesis that organic sand grains with equilibrium sizes may instead result from an interplay between alternating episodes of sintering (when sand is immobile) and abrasion (when active fluvial or eolian transport occurs).

Methods: The model of [13] provides estimates of abrasion rate of individual impacting particles during fluvial sediment transport, including both bedload and suspended load sediments. We adjusted the model of [13] for Titan-relevant conditions and materials and predict particle-size reduction rates of organic grains in streams of CH_4/N_2 mixtures [14]. Owing to Titan's thick atmosphere, windblown sand transport is expected to be more analogous to sand transport by water on Earth than by air on Earth and Mars, with minimal importance of grain splash [7] (unless sand is highly cohesive [8], in which case our scaling relationship for aeolian abrasion rates provides an estimate of abrasion rate for the saltating grain population). We thus obtain estimates of eolian abrasion rates from fluvial abrasion rates through a scaling analysis and accounting for typical saltation trajectories on Titan as predicted by [7]. In turn, the sintering scaling relationship of [15] predicts the time it takes for a cluster of particles to sinter into a larger particle.

Results & Discussion: Our results suggest that intermittent grain sintering, when grains are at rest, is most likely required to counterbalance the effect of intermittent abrasion during transport in order for Titan's dunes to have persisted to this day. Our model predictions are consistent with geologic constraints on estimated grain sizes in the dune fields, the frequency of methane rainstorms and sand-transporting winds, and is readily able to explain the latitudinal zonation of Titan's landscapes. Our findings support the hypothesis of global, source-to-sink sedimentary pathways on Titan, driven by seasonal climate forcing, and mediated by episodic abrasion and sintering of organic sand grains by rivers and winds.

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A CROSS-LABORATORY COMPARISON STUDY OF TITAN HAZE ANALOGS: SURFACE ENERGY

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Introduction: In Titan's nitrogen-methane atmosphere, photochemistry leads to the production of complex organic particles, forming Titan's thick haze layers. Laboratory-produced aerosol analogs, or "tholins", are produced in a number of laboratories; however, most previous studies have investigated analogs produced by only one laboratory rather than a systematic, comparative analysis. In this study, we performed a comparative study of an important material property, the surface energy, of seven tholin samples produced in three independent laboratories under a broad range of experimental conditions, and explored their commonalities and differences.

Methods: Two tholin samples were produced in the Planetary Haze Research (PHAZER) chamber at Johns Hopkins University (JHU) from an initial N_2:CH_4 (95:5) gas mixture using two energy sources: an AC glow discharge and a hydrogen UV Lamp [1]. Four tholins samples were produced in the Cosmic Simulation Chamber (COSmIC) at NASA Ames Research Center (ARC) using a cold plasma discharge as the energy source [2] and four different initial gas mixtures: N_2:CH_4 (95:5), N_2:CH_4:C_2H_2 (94.5:5:0.5), Ar:CH_4 (95:5), and Ar:CH_4:C_2H_2 (94.5:5:0.5). One tholin sample was produced in the Photochemical Aerosol Chamber (PAC) at University of Northern Iowa (UNI) [3] from an initial gas mixture of N_2:CH_4 (95:5) using a deuterium lamp as the energy source.

To measure the surface energy of a tholin sample, a droplet of a test liquid is dispensed onto the sample, using a microsyringe, to form a sessile drop. The test liquids used are HPLC-grade water (FisherChemical™) and diiodomethane (>99%, ACROS Organics™). Each drop process is recorded as video using an Ossila goniometer. Contact angles are then measured by both the Ossila software and contact angle plugin of the ImageJ software. A comparison test confirmed Osilla and ImageJ return similar contact angle values and can be used interchangeably. The Owens-Wendt-Rabel-Kaelble (OWRK) and Wu analytical methods are then used to estimate the surface energies of each tholin from contact angle measurements. Both assume the surface energy and surface tension can be partitioned into a dispersive component and a polar component. All experiments are performed inside a dry glove box (relative humidity RH <1%) flowed with 99.999% purity dry nitrogen.

Results and Discussion: All tholin samples are found to have high surface energies as shown in Table 1, and are therefore highly cohesive. Thus, if the surface sediments on Titan are similar to tholins, future missions such as Dragonfly will likely encounter sticky sediments. We also identified a commonality between all the tholin samples: a high dispersive (non-polar) surface energy component of at least 30 mJ/m^2. This common property could be shared by the actual haze particles on Titan as well. Given that the most abundant species interacting with the haze on Titan (methane, ethane, and nitrogen) are non-polar in nature, the dispersive surface energy component of the haze particles could be a determinant factor in condensate-haze and haze-lake liquids interactions on Titan. With this common trait of tholin samples, we confirmed the findings of a previous study by [4] that haze particles are likely good cloud condensation nuclei (CCN) for methane and ethane clouds and would likely be completely wetted by the hydrocarbon lakes on Titan.

Table 1: Derived surface energy of tholins produced with different experimental setups and methods (all units in mJ/m^2). The total surface energy γ_s^{tot} can be divided into the dispersive, γ_s^d, and polar, γ_s^p, components.

Samples	*OWRK Method*		
	γ_s^d	γ_s^p	γ_s^{tot}
JHU-UV N_2-CH_4	31.5	16.2	47.7
JHU-Plasma N_2-CH_4	37.4	35.9	73.3
ARC N_2-CH_4	45.7	20.6	66.3
ARC N_2-CH_4-C_2H_2	44.4	9	53.4
ARC Ar-CH_4	48.3	0.4	48.7
ARC Ar-CH_4-C_2H_2	47.5	1.7	49.2
UNI-UV N_2-CH_4	33.9	19	52.9

References:

[1]He, C. et al., (2017). *ApJL*, 841, L31. [2]Sciamma-O'Brien et al., (2017). *Icarus,* 289, 214. [3] Sebree, J. A. et al., (2018). J. *Photoch. Photobio.* A, 360,1. [4] Yu et al.,(2020).*ApJL*, 905(2), 88.

TITAN'S WIND FIELD AROUND EQUINOX FROM eSMA MEASUREMENTS. S. L. Light[1,3], M. A. Gurwell[2], C. A. Nixon[3], A. E. Thelen[3], [1]University of Maryland, College Park, MD 20742, USA (slight@umd.edu) [2]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA [3]Planetary Systems Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Introduction: Measurements of Titan's winds are of ongoing scientific interest due to the insights these can provide into the underlying dynamical processes in its atmosphere [1]. At present, seasonal changes in the wind speeds, especially at higher altitudes, are poorly constrained [2]. The molecule acetonitrile (CH_3CN) was used in the first direct determination of mesospheric wind speed on Titan, accomplished using Doppler line shift measurements with data acquired by the IRAM 30-m telescope [3]. The zonal wind direction was found to be in a prograde direction and further studies have provided agreement with this result [3, 4, 5]. In this study, data taken shortly before and after Titan's last equinox in 2009 and 2010 was analyzed to expand the time series of CH_3CN abundances and wind speed measurements on Titan, and determine any changes that have occurred during this time period, which is known to exhibit abrupt changes [6].

Observations: The extended Submillimeter Array (eSMA) was used to conduct interferometric observations of Titan on 2009 March 23 and 2010 February 12 at a rest frequency of 349.415 GHz and channel resolution of 203.1 kHZ [2]. In 2009, 8 SMA antennas (6-m diameter), the James Clerk Maxwell Telescope (JCMT) single-dish antenna (15-m diameter), and the Caltech Submillimeter Observatory (CSO) single dish (10.4-diamaeter) were used for the observations resulting in a combined baseline of 780 meters. For the 2010 observations, the combined baseline of 625 meters was the result of using 7 SMA antennas and the single-dish JCMT. Further observational details are described in [2].

To calibrate the data, standard methods in interferometric data reduction were employed[1]. Further calibration details are also outlined in [2]. The image of Titan in 2010 was expanded to have the same apparent size as Titan in 2009 for more direct comparison purposes. Spectral cubes of the two data sets were made for 2009 and 2010 with the frequency axis adjusted to be in the Titan rest frame. The 2009 data consisted of 448 channels with a resolution of 0.203125 MHz and a rest frequency of 349.366798438 GHz, while the 2010 data had the same amount of channels and channel resolution but a rest frequency of 349.366293083 GHz.

Analysis: During an early analysis of the 2009 data, CH_3CN abundance was observed to roughly increase with altitude, with an abundance enhancement at northern high latitudes by at least a factor of three, consistent with other nitriles [7]. Integrated maps of the continuum subtracted flux across the full spectra of both observational years were constructed, shown in Figure 1. The magnitude of velocity measurements remains a work in progress.

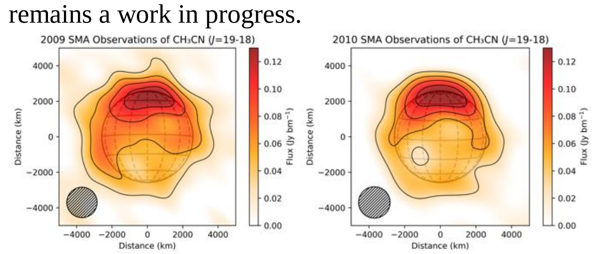

Figure 1: (Left) Integrated continuum subtracted CH_3CN emissions map for 2009 (left) and 2010 (right) with the image convolved to a 0.28" circular beam shape. Contour intervals are based on percentiles of the maximum flux. Emissions appeared to be more constrained to northern latitudes for 2010 relative to 2009.

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Dynamical Simulations of Titan's Stratosphere using Observationally Derived Molecular Abundance and Aerosol Opacity. N. A. Lombardo[1] and J. M. Lora[1], [1]Department of Earth and Planetary Sciences, Yale University, nicholas.lombardo@yale.edu

Introduction: The ultimate driver of Titan's atmospheric circulation is radiant energy delivered from the sun, which, as on Earth, causes meridionally differential heating [1]. The radiative heating (and cooling) of Titan's atmosphere is controlled by the presence of visible and infrared-active molecules, aerosols, and collision-induced absorption from temporary dimers (such as N_2-N_2 and CH_4-CH_4). Access to accurate maps of trace species and aerosols on Titan is therefore necessary to provide the most robust starting point for General Circulation Model (GCM) calculations.

Previous studies have made progress studying Titan's radiative balance either from single *in situ* measurements from Huygens [2] or a collection of low-latitude Cassini observations [3]. Since these studies, new spectroscopic parameters for molecules present in Titan's atmosphere have been determined, and comprehensive datasets of the seasonal variations of Titan's atmospheric composition have been created.

Critical to Titan's atmospheric thermal structure is the absorption of visible (and emission of infrared) energy by aerosol particles. Titan exhibits seasonal variations in aerosol opacity in its upper stratosphere and mesosphere, most notably in a region of depleted aerosol effects at summer latitudes between about 300 km and 500 km. The depleted zone leads to an apparent "Detached" Haze Layer (DHL) above these altitudes that rejoins the main haze as the summer latitudes progress through autumn and winter. A recent study has made available nearly-global measurements of aerosol opacity at these altitudes during Cassini flybys of Titan between 2004 and 2017. [4]

Here, we present ongoing work incorporating these newly released extensive datasets of Titan's atmospheric composition with a radiative transfer scheme to study the effects of Titan's seasonally varying radiative balance on its dynamical phenomena.

Observations: The end of the Cassini mission has left the Titan community with a plethora of observations acquired in a multitude of observing geometries [5]. Certain nadir observations enabled large swaths of Titan's disk to be mapped during a single flyby, allowing for an in-depth coverage of Titan's meridional variations near 100 km (low stratosphere), at the expense of vertical resolution. Alternatively, limb-viewing geometries provided ~40 km vertical resolution between 100 km and 500 km in Titan's middle atmosphere, though these observations were less frequent and provided less spatial coverage. Recent analyses of the complete set of Cassini observations have provided us with unprecedented looks at Titan's ever-changing atmospheric chemistry in separate horizontal [6] and vertical [7] domains.

Photochemically active molecules that are short-lived (for example HCN, C_4H_2, and CH_3C_2H) tend to show steep meridional gradients, with significantly higher concentrations found near the winter pole due to confining effects of the winter polar vortex. Molecules that are more stable, such as C_2H_6, show little meridional and seasonal variations, and tend to take an approximately constant vertical profile across Titan.

Visible observations from the Visible and Infrared Mapping Spectrometer (VIMS) were utilized to map the visible opacity of aerosol particles between about 300 km and 500 km, allowing for the radiative effects of Titan's seasonally varying Detached Haze Layer (DHL) to be included in our GCM [4].

Model: The Titan Atmospheric Model (TAM; [9]) is a 3-dimensional GCM of Titan's atmosphere that has been used previously to study several aspects of Titan's lower atmosphere. In this ongoing study, we modify TAM's 1-dimensional radiative transfer model to include recently updated spectral properties of Titan's atmospheric constituents from the HITRAN database, and recalculated aerosol optical properties [10].

We employ our updated model to simulate Titan's stratosphere as it progresses through a full year, using atmospheric compositions derived from observations of seasonal changes [6, 7], for example considering polar wintertime enhancements [6]. The observationally derived molecular abundance and aerosol radiative properties enable us to accurately include radiative heating rates on Titan to understand the effects of seasonally-varying radiative forcing on Titan's stratospheric dynamical phenomena.

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HABITABILITY OF HYDROCARBON WORLDS: TITAN AND BEYOND. R.M.C. Lopes[1], M.J. Malaska[1], and the Titan NAI Team, [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109 (rosaly.m.lopes@jpl.nasa.gov)

Introduction: Titan is an ocean world, an icy world, and an organic world. Recent models of the interior suggest that Titan's subsurface ocean may be in contact with an organic-rich ice-rock core, potentially providing redox gradients, heavier elements, and organic building blocks critical for a habitable environment. Further above, at the contact of the ice shell and ocean, Titan's abundant surface organics could be delivered to the aqueous environment through processes such as potential convective cycles in the ice shell. Above the subsurface ocean, liquid water resulting processes such as cryovolcanic activity, diapiric rise, or from impact melt could create transient habitable environments. Our work investigates the pathways for atmospheric organic products to be transported from the surface to the ocean/core and the potential for ocean/deep ice biosignatures and organisms to be transported to the shallow crust or surface for interrogation and discovery. Our major objectives are: (i) Determine the pathways for organic materials to be transported (and modified) from the atmosphere to surface and eventually to the subsurface ocean (the most likely habitable environment). (ii) Determine whether the physical and chemical processes in the ocean create stable, habitable environments. (iii) Determine what biosignatures would be produced if the ocean is inhabited. (iv) Determine how biosignatures can be transported from the ocean to the surface and atmosphere and be recognizable at the surface and atmosphere.

Summary of progress: We have made significant progress on photochemical and dynamical modeling of Titan's atmosphere. On the observational side, analysis of ALMA data resulted in the first observation of the CH_3D molecule at sub-millimeter wavelengths [1]. Analysis of NASA IRTF data resulted in the first detection of propadiene (CH2CCH2) in Titan's atmosphere [2]. Spatial and seasonal changes in Titan's gases from the final years of the Cassini mission were the subject of several papers, using data from ALMA [3] and CIRS [4,5]. On the modeling side, coupling two atmospheric models that cover different altitudes in Titan's atmosphere allowed integration of the entire atmosphere of Titan. In order to understand how materials falling from the atmosphere are transported across the surface, we are developing a landscape evolution model, which involved re-writing and optimizing the DELIM code that is used for Mars. We have published the first global geomorphologic map of Titan [6] which will serve as a constraint for the landscape evolution model by showing how sedimentary and depositional materials are distributed over the surface. We obtained an updated estimate of the amount of organic materials on Titan, which is important as a constraint on the amount of chemical energy and building blocks available for potential life. To investigate the molecular pathways from surface to subsurface ocean, we have performed a series of numerical simulations on the effect of a clathrate layer capping Titan's icy crust on the convection pattern in the stagnant lid regime [7]. In the investigation of habitats resulting from molecular transport, we have modeled the accretion of Titan to understand the effects of thermal evolution on the rocky interior, and to constrain the composition of volatiles exsolved from the interior and that may have migrated vertically to build up the ocean early in Titan's history [8]. We have also published results of modeling water-hydrocarbon mixtures using the CRYOCHEM code, which now successfully allows chemical modeling of both the hydro-carbon-rich condensed fluid phases and the water-rich condensed fluid phases (and vapor phases, too) simultaneously [9]. Preliminary results for our investigation of ocean habitats led to new insights into the origin of methane and nitrogen (N2) on Titan by modeling D/H exchange between organics and water, as well as high pressure C-N-O-H fluid speciation in Titan's rocky core [10]. Results suggest an important role for organic compounds in the geochemical evolution of Titan's core, which may feed into the habitability of Titan's ocean.

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GLOBAL INFLUENCES OF POLAR STORMS IN SIMULATIONS OF TITAN'S CLIMATE. J. M. Lora[1] and J. M. Battalio[1], [1]Department of Earth and Planetary Sciences, Yale University, 210 Whitney Ave, New Haven, CT 06511, juan.lora@yale.edu

Introduction: Titan is known to harbor a rich hydroclimate, complete with myriad surface geomorphologic expressions like high-latitude methane seas [1], evaporation therefrom, atmospheric moisture transport, and tropospheric cloud activity and precipitation [2]. Observed cloud activity has been clearly linked to Titan's long seasonal cycle [3], yet the variability of precipitation at other timescales, and its driving mechanisms, remain relatively unexplained.

Multiple cloud features observed on Titan have been reported to be nearly stationary, despite in some cases being long-lived [4]. Given their occurrence in otherwise westerly flow, particularly at mid- and high latitudes, this stationarity might imply some coupling to waves in the atmosphere. On the other hand, waves have been invoked to explain low-latitude cloud outbursts and subsequent mid-latitude activity [5,6], yet the possible connection between high-latitude atmospheric waves and stationary clouds over Titan's poles has not been directly addressed.

Climate simulations: To address this gap, we investigate the development of convective events in the coupled version of the Titan Atmospheric Model (TAM) [7]. This version of TAM comprises coupled atmosphere–land hydrology models that enable a self-consistent representation of the methane hydrologic cycle on Titan [8]. In addition, we have tuned the model's moist convection parameterization, guided by observations and cloud-resolving simulations.

To study robust features of convective storm development, we select the 48 largest convective events in the northern hemisphere across 15 Titan years of simulations, averaging over the events (after shifting to a common relative longitude) for the 30 Titan days (Tsols) before and after the time of maximum precipitation.

Results: In our composite results, Rossby waves propagating east with the mean flow at high latitudes coincide with convective instability to trigger the storms. For several Tsols following the onset of precipitation, the original wave is halted through its interaction with the convection, implying multi-Tsol, stationary cloud events. At the same time, the wave, amplified by the convection, extends to lower latitudes and excites a southern-hemisphere wave. Some Tsols later, the two waves phase-lock, and the southern portion eventually decays. The whole process takes some tens of Tsols.

Importantly, in addition to providing a potential explanation for observed stationary clouds on Titan, the results imply that such storm events have the potential to affect most of Titan's globe: First, the released latent heat increases the outgoing longwave radiation, and this is quickly communicated globally by the waves. Additionally, meteorological fields near the surface at low latitudes also respond; specifically, periodic surface pressure changes with amplitudes of tens of Pa are simulated, along with variations in temperatures, humidity, and winds.

While the TAM simulations are idealized in many ways, our results offer predictions that will allow testing whether these globally-impactful storms are a robust feature of Titan's climate. Even at low latitudes, the meteorological instruments carried by *Dragonfly* could detect the associated perturbations. *Dragonfly* is slated to arrive at Titan around the start of southern summer, just when (southern) polar convection should be expected to begin.

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MISSION INCREDIBLE: A TITAN SAMPLE RETURN USING IN-SITU PROPELLANTS

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Introduction: Titan is unique in the outer solar system in that it is the only moon with a thick atmosphere, and the only body in the solar system outside the Earth with liquid seas on its surface. The Titanian oceans, however, are seas of liquid hydrocarbons, and the rocks on the surface are solid water ice. Many studies of space development emphasize use of the in-situ resources to eliminate the requirement to launch propellants from Earth. With water, liquid methane, and ethane easily available, Titan is a rocket scientist's dream for propellants, as recognized by Arthur C. Clarke and others.

Such a sample return would truly be "mission incredible". But to date, a sample return mission from so distant a target has been assumed to be, not merely incredible, but mission impossible. Our task, supported by the NASA Innovative Advanced Concepts (NIAC) program ,is to show that it is credible with near-term space technology.

Architecture: The study is presently underway, and a number of open trades exist. One important development is the recognition that acquiring liquid methane from the seas is not actually necessary, and is in fact rather geographically restrictive. Instead, simple thermodynamic processing (analogous to running a domestic dehumidifier on Earth) can easily condense methane out of the atmosphere, at any location.

It is assumed that the mission can access water-ice-dominated surface material that can be excavated, melted, and electrolyzed to yield oxygen. Titan temperatures permit this oxygen to be easily stored in liquid form. The electrolysis process is energy-intensive, and becomes (depending on the radioisotope or fission power source used) the rate-limiting step in the in-situ propellant production. Possible landing sites considered are the Selk impact crater (target of Dragonfly, and known to have some water-bearing material exposed) and the Doom Mons candidate cryovolcano.

LOX/Methane is a high-performance rocket propellant combination, with a specific impulse around 325s. A rough calculation was performed to see just how much propellant is needed to return samples to the Earth. Previous studies suggest ascent and Earth-return ΔVs required are around 3300 m/s and 4600 m/s respectively. We assume a 60-kg Earth return vehicle (12 km/s hyperbolic arrival velocity) similar to Stardust and an 80 kg, Stirling generator-powered cruise deck. It is assumed that the scientific integrity of the sample requires that it be maintained at cryogenic temperatures all the way back to Earth (prompt recovery of the sample capsule after landing will be essential.)

While the three-stage vehicle's mass is quite large, only around 1000 kg needs to be landed, with the mission acquiring over 3500 kg of propellants from Titan.

The Titan ascent trajectory is an interesting new problem, in that the gravity and drag losses are quite different from those of terrestrial launch vehicles.

Conclusion: The design study is presently underway (mid/late July) and results will be presented at the Titan Through Time meeting.

PROSPECTS FOR YARDANGS ON TITAN. S. M. MacKenzie[1], K. Runyon[1], J.F. Kok[2], C. Newman[3], X. Yu[4] [1]Johns Hopkins Applied Physics Laboratory (shannon.mackenzie@jhuapl.edu), [2]UCLA, [3]Aeolis Research, [4]UCSC

Introduction: Titan's water-ice crust is littered with sediments. The vast sea of longitudinal dunes that almost entirely encircle the moon's equator [1,2] hosts 100,000s km^3 of organics [3]. Other organic sediments are created by lacustrine processes [4-5] while fluvial processes may carve water-ice rich clasts [6-10].

With both active aeolian processes and an abundance of sediment available, it is therefore perhaps unsurprising that putative yardangs have also been identified on Titan's surface [11,12]. Titan's candidate yardangs resemble terrestrial examples [11], though they have also been interpreted as stabilized linear dunes. These features lie primarily in the mid-latitude regions, far from the equatorial sand seas. These "blandlands", which make up ~65% of Titan's surface area, are hypothesized to host organic sediments [13-15] though their provenance and composition remain unknown. Thus, the prospects for yardang formation on Titan remains shrouded in questions. Are materials anticipated on Titan amenable to abrasion? Are the winds strong/frequent enough to create the features observed?

In this work we seek to describe possible scenarios of abrasion on Titan. A grand unified theory of yardang formation and evolution remains elusive, but several key factors of the process have been identified, including the kinetic energy of impactors [16], mechanical properties of the host lithology and the ablators [17-19], and sediment availability in the corridors [20]. We investigate these factors for a suite of possible scenarios with combinations of water ice and organic as the targets and/or saltating material.

Methods: It is generally agreed that the rate of abrasion scales with the kinetic energy of the impactor. [21] derived an expression for the rate of abrasion (m/s) at a height above the floor as a function of both the impactor kinetic energy and the strength of the target rock. By taking the time average, we can find the long-term rate of wind abrasion:

$$\Phi_z = 6k\frac{\rho}{S_c}\sum_i q_{z(i)}U^2_{s,z(i)}T(i)$$

where the duration of winds *T(i)* at a given velocity interval, *i*, weights the efficacy of abrasion. *k* is a dimensionless empirical constant, ρ is the sand particle density (kg/m^3), q_z is the sand supply rate (m^3/s), U_s is the particle velocity (m/s), and S_c is the strength of target rock (N/m^2).

Inputs to these equations are derived from two models. We estimate the intensity and frequency of winds across Titan's surface over a full annual cycle using TitanWRF, a 3D general circulation model of Titan's atmosphere [22]. Kinetic energies of impactors and vertical flux profiles are derived from COMSALT, a physics-based numerical model of steady state saltation [23] for a range of particle densities and impact velocity thresholds.

Results: Figure 1 shows TitanWRF predictions for u*, the friction velocity, at different locations on the surface of Titan. The blandlands, where the yardang candidates are found, have a different frequency distribution than the dune fields. These frictional velocities are used to define the intermittency of impact threshold velocities (and thus the duration of winds T_i)

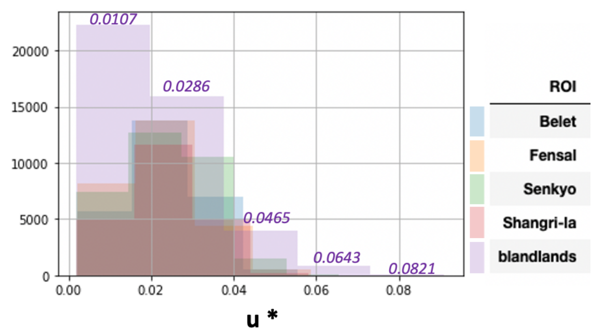

Figure 1: TitanWRF predictions for frequency of occurrence (y-axis) of $u*$ (m/s; x-axis) over 1 Titan year.

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DRAGONCAM SCIENCE OBJECTIVES AND STATUS UPDATE. S. M. MacKenzie[1], J. Linden[1], S. Murchie[1], M.A. Ravine[2], J. Nunez[1], C. Ernst[1], and the DragonCam Team, [1]Johns Hopkins Applied Physics Laboratory (shannon.mackenzie@jhuapl.edu), [2]Malin Space Science Systems

Introduction: Dragonfly will revolutionize our understanding of Titan by determining the specific chemical composition of surface clasts with mass spectrometry [1-4]. But which materials should we excavate and ingest? What is their provenance? Where should Dragonfly land next if we want to sample different material? DragonCam, a suite of cameras, will serve as Dragonfly's eyes on the ground and in the air, providing the data necessary to answer these questions from the ground and air.

A nested scale approach: DragonCam consists of 8 science cameras (Figure 1). Two Panorama Cameras are the only cameras housed outside the lander. Mounted on the High Gain Antenna, the Panorama Cameras can be articulated to build up the scene around the lander. Two Forward Cameras image the foreground in stereo thanks to with overlapping fields of view. Two Downward Cameras each cover an area at least 1 m^2 beneath the lander, which includes the skids, the drills, directly beneath the forward rotors, and the deployed seismometer. Overlap between the Downward Cameras will facilitate stereo imaging at the sub-mm scale. Each drill site is also targeted by a Microscopic Camera with spatial sampling fine enough to resolve anticipated sand grain sizes (a few 100 um). The Microscopic Cameras effectively have "stereo" capabilities independently: images taken at successive focus distance, z-stacking, convey microtopography.

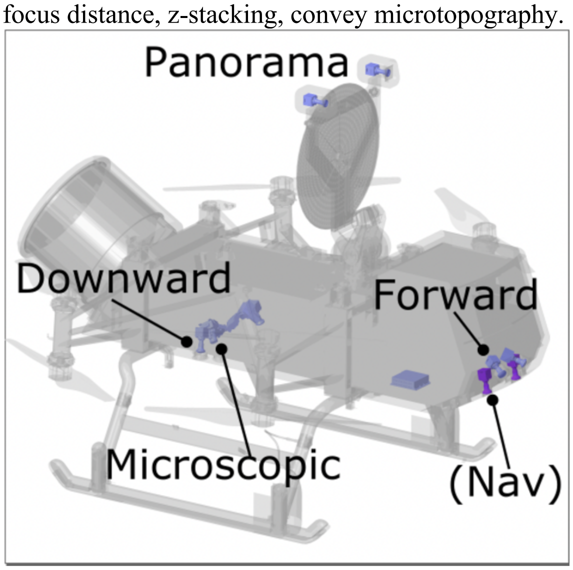

Figure 1: *Current configuration of DragonCam. Exact positions may change as the lander design evolves, but the relative positions are set by each set of cameras' purpose.*

Terrain Relative Navigation is facilitated by a separate set of cameras, NavCam, which are specifically optimized for acquiring and processing in-flight images.

Color imaging: We seek to maximize interpretability across these different scales by employing the same detectors and filters in each camera. The science cameras use an Bayer-pattern of RGB filters to image the surface in visible color. Reconstruction of the color image relies on interpolation, providing additional information for exploring the surface composition at the cost of some effective resolution, An array of LEDs can illuminate the drill site and may facilitate constructing "spectra" with independent illumination in 9 colors [5]. One LED color will be in the UV to look for stimulated fluorescence [6]. Three calibration targets will be mounted on the lander, one within the field of view of the Panorama Cameras and one in the field of view of each of the Downward Cameras.

Science investigations: DragonCam provides key context to the sampling investigation by enabling the team to map from the granular scale of excavated samples to the terrain surrounding the lander and infer the geological processes at work. Images will also be taken to assess whether small scale features like ripples have moved in response to gusts (natural or Dragonfly-made). Many planned datasets serve both a science and tactical purpose. Illuminating and imaging the drill site, for example, not only allows for characterization of sand grains, but also helps diagnose if material is too wet to sample via specular reflections.

Protecting the windows: Each of Dragonfly's cameras are separated from the Titan environment by a sapphire window coated with indium tin oxide and fluorosilane. This coating has been shown to prevent fouling in laboratory simulations with Titan-analog materials [7].

Data return: Thumbnail images will be downloaded and shared publicly upon receipt. Compression schemes must be employed for efficient data return but raw images are stored on the recorder for later downlink, as possible/desired.

Acknowledgments: This work was funded by the Dragonfly Project.

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RAPID FLUVIAL ABRASION IN THE TITAN TUMBLER. A. M. Maue[1], D. M. Burr[1], J. S. Levy[2], P. R. Matulka[3], and E. Nathan[4], [1]Northern Arizona University (Flagstaff, AZ; maue@nau.edu), [2]Colgate University (Hamilton, NY), [3]Washington University in St. Louis (St. Louis, MO), [4]Brown University (Providence, RI).

Introduction: Laboratory studies are a common approach to understanding sedimentary processes on Earth and can likewise be helpful for understanding analogous processes on Titan. Tumbling mills used in terrestrial studies reproduce some important aspects of mechanical weathering for sediment in fluvial transport [1]. Such weathering may explain the rounded clasts imaged at the Huygens landing site (HLS, [2]) and suggested by the anomalous radar backscatter of some fluvial features [3]. Our icy abrasion experiments explore sediment processing at cryogenic temperatures and fluvial features as a sand source for Titan's vast dunes.

Methods: A 15-cm-diameter polyvinyl chloride (PVC) rotating drum was used to tumble H_2O ice clasts at ~195 K (CO_2-cooled) and ~100 K (N_2-cooled). Rotation speeds were adjusted to promote clast interactions involving the rolling and hopping typical of bedload transport. Centimeter-scale ice clasts were made from freezing deionized and degassed H_2O at 253 K before cooling down to tumbling temperatures. Initial clast conditions were varied in size, shape, and crystallinity (either frozen into polycrystalline "igneous" ice or grinded and cemented into monocrystalline "sandstone" ice). Most experiments ran for >1 km, with some out to 10s of km. Tumbling was halted at regular intervals for sieving, weighing, and imaging of clasts to record mass-loss, grain size distribution, and shape (roundness index $= 4\pi A/P^2$, as in [4]).

Results: *Comparisons to terrestrial sediment.* For this work we consider abrasion (mass-loss by mechanical wear) as a combination of attrition (fines lost from the surface of clasts) and fragmentation (clasts split into multiple pebbles). Total mass-loss and rounding both decreased at colder temperatures (~100 K), possibly due to the greater tensile strength of colder ice [5]. However, greater fragmentation occurred at these colder temperatures. This result may partly be due to thermal stresses during measurements, but even clasts in more gradually cooled experiments had >50% of their abrasion as fragmentation—in contrast to the slow attrition seen with many terrestrial lithologies [1].

Overall abrasion rates were comparable to that of the weakest terrestrial lithologies in previous studies (Fig. 1). Furthermore, the trends of mass-loss over distance are not well-predicted by a classic exponential abrasion model [7], but are better fit by the multi-stage model of [8]. Despite fragmentation producing planar clast surfaces, high roundness indices (>0.9) were reached after only a few km in the tumbler.

Effects of specific initial clast conditions. Initial clast size, shape, and crystallinity were varied throughout our tumbler experiments. Normalized mass-loss increased with initial clast size (varied 0.8 to ~7 cm), as seen in terrestrial tumbler studies with well-sorted grains [6]. Sets of 4 or 6 cube-shaped initial clasts produce repeatable trends, whereas clasts beginning with more angular, random shapes varied significantly and don't show a strong control by initial shape.

Ice clasts frozen to be more monocrystalline vs polycrystalline don't show a clear difference in rounding or mass-loss. Furthermore, the grain size distribution of fines produced by abrasion was not correlated to the ice crystal size selected for, possibly due to clast breakage occurring indiscriminate of grain vs matrix.

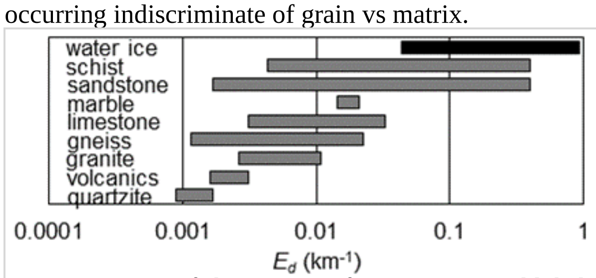

Figure 1. Range of abrasion rates for some terrestrial lithologies (gray, [6]) compared to ice in the Titan Tumbler (black). Abrasion rate, E_d, is computed as $\ln(M_0/M)/L$, where L is distance travelled and M_0 and M are the mass initially and at L.

Conclusions: The mechanical breakdown of water ice clasts during fluvial transport on Titan may be akin to that of relatively weak sedimentary rocks on Earth. Despite rapid fragmentation, ice clasts reach roundness indices comparable to HLS clasts in just a few km. Resulting grain size distributions suggest fluvial abrasion is not a significant contribution to Titan's sand seas. Continued lab experiments, e.g., with more precise correlation to theoretical bedload transport speed, will be critical for constraining Titan's sedimentary processes. The full results of various iterations of Titan Tumbler experiments will soon be published online [9,10].

Acknowledgments: This research is supported by NASA SSW grant NNX16AG09G to JSL and DMB.

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Structural Investigation of High-Temperature Polymorphs of Propionitrile Ice. C. A. McConville, Department of Chemistry, Southern Methodist University, Dallas, TX 75275 (USA). Email: cmcconville@smu.edu

To study the formation of potential minerals on Titan, we analyze structural and physicochemical information of the constituents present on Titan's surface. Among these compounds is propionitrile, whose crystal structure remained unknown until recently. Although a crystal structure of propionitrile was published in January 2020, questions still remain about the chemical behavior of this elusive nitrile ice. Our calorimetric data and synchrotron powder diffraction data both indicate the presence of two additional high-temperature phases. We perform structure solution of this compound using X-ray diffraction techniques, supported by single-crystal diffraction, neutron diffraction, differential scanning calorimetry, and Raman spectroscopy. Our ongoing studies confirm the crystal structures of these two additional phases and demonstrate the need for further physicochemical characterization of propionitrile.

REVIEW OF CURRENT CONSTRAINTS ON THE ORIGIN OF TITAN'S ATMOSPHERE.

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The origin of Titan's atmosphere has been a longstanding question in planetary science, with implications for formation of the Saturnian system as well as volatile cycles and evolution throughout the outer solar system. Titan's primary atmospheric constitutents, CH_4 and N_2, were first identified via the McDonald Observatory [*1*] and the Voyager flyby [*2*] respectively. Understanding of the origin of these compounds and Titan's atmosphere as a whole continued to evolve throughout the Cassini mission, and to the present day. In this presentation, I will review evolving understanding of the origin of Titan's atmosphere and highlight related open questions.

From Voyager data, the mean molecular mass of Titan's atmosphere was found to be too high for the atmospheric composition to be explained by simple capture of unfractionated gas from a nebular disk, since N_2 and Ne have similar solar abundances [*3*]. Early theoretical models instead suggested that CH_4 and NH_3 were the dominant C- and N-bearing phases at the pressure and temperature conditions hypothesized for the Saturnian sub-nebula [*4, 5*]. Shock and/or photolysis processes were suggested to convert NH_3 to N_2, with production of H_2 (another atmospheric constituent) as a byproduct [*5, 6*]. However, conversion of NH_3 to N_2 in the interior and subsequent outgassing was suggested to circumvent the high surface temperatures required for release of NH_3 to the atmosphere [*3*]. Measurement of a low $^{36}Ar/^{14}N$ ratio as well as non-detections of Kr and Xe via the Huygens probe GC-MS [*7*] have been interpreted as evidence for accretion of temperature-fractionated volatiles [*8, 9*], consistent with accretion of N in a form more refractory than N_2, such as NH_3. Isotopic constraints from N_2 were found to be more consistent with origination from protosolar NH_3 ice rather than N_2 ice [*10*], including consideration of nitrogen isotopic evolution of the atmosphere [*10-12*].

Photolytic destruction of methane with irreversible loss of hydrogen on geologically short timescales was identified as an important constraint [*13*], and outgassing of methane from Titan's interior was identified as a potential solution [*14, 15*]. Volatile release from Titan's interior was found to be consistent with constraints on the abundance and isotopic characteristics of CH_4, N_2, and noble gases if Titan's building blocks were a mixture of CI chondrites plus ices fractionated in a warm Saturnian subnebula [*16*]. Results from the Rosetta mission confirmed previous measurements at Halley's comet that suggest refractory organic material was a major component of outer solar system building blocks [*17, 18*]. This organic material had previously been suggested as a potential N reservoir for the outer solar system [*19*], and geochemical modeling at Titan suggests based on isotopic and $^{36}Ar/N$ constraints that volatilized organics may contribute as much as 50% of Titan's atmosphere given appropriate interior conditions [*20*].

Open Questions: While understanding of the origin of Titan's atmosphere has evolved considerably since its discovery, open questions remain. These questions include:

- Over what timescales has Titan's atmosphere been stable?
- What roles have photolysis and outgassing processes played in the evolution of Titan's atmosphere?
- If outgassing was an important process, how does Titan's atmosphere constrain time, temperature, and geochemical conditions in Titan's interior? How do these conditions relate to habitability?

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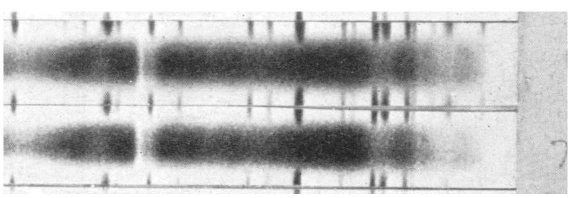
TANGERINE DREAM: OBSERVATIONS OF TITAN FROM THE EARTH. C. A. Nixon[1], [1]Planetary Systems Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. conor.a.nixon@nasa.gov

Abstract: From its discovery in 1655 by the Dutch astronomer Christiaan Huygens, Titan perplexed and confounded Earth-based astronomers for three centuries with its stubborn refusal to yield virtually any clues about its nature. Until the Voyager 1 1980, even fundamentals such as its true diameter, surface pressure, and major atmospheric gas were uncertain [1]. Most of the information we now know about Titan has been wrestled at great expense of time and effort by three spacecraft visitors: *Voyager 1, Cassini* and *Huygens*. So why then continue to bother with Earth-based telescopic observations?

In this review talk I will describe how significant clues about Titan's atmospheric composition began to emerge from ground-based observations in the 1940s through 1970s, in the run-up to the revolutionary *Voyager 1* flyby. These included the discovery of methane [2], and other significant hydrocarbons including ethane and acetylene in Titan's stratosphere [3, 4]. Further ground and space-based telescopic work in the 1980s and 1990s revealed the presence of the fourth most abundance gas, carbon monoxide [5], spotted for the first time the bright continent on Titan's leading hemisphere now known as Xanadu [6], and the comings and goings of bright tropospheric clouds [7].



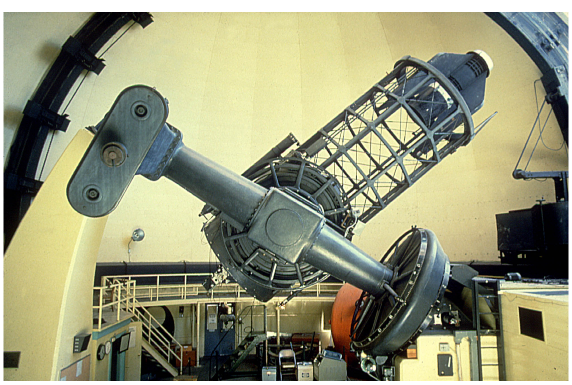


Figure 1: Upper – discovery of Titan's atmosphere by Kuiper (1944) [2]. Two spectra of Titan in the near-infrared are shown, bracketed by reference fiducial marks from the spectrum of methane gas. Lower – the 82 inch reflecting telescope at McDonald Observatory used to make the measurements in the winter of 1943-1944. (Image credit: McDonald Observatory)

The *Cassini-Huygens* mission of 2004-2017 [8, 9] greatly expanded our knowledge of Titan, including the first in situ measurements of the atmosphere and detailed imaging of the surface. However in the two-decades long gap before the next mission, *Dragonfly*, reaches Titan we are finding new ways to further our knowledge of Titan using the current generation of telescopes and instruments. With high-resolution spectroscopy at infrared and sub-millimeter wavelengths we are finding new chemical constituents in the atmosphere, and even measuring wind fields at middle altitudes.

I will conclude by discussing how the next generation of Earth and space-based telescopes and instruments promises yet more breakthroughs via astronomy, including with large aperture 30 and 40 meter class telescopes that will become available in the late 2020s, and spectroscopy with airborne and space telescopes such as *SOFIA* and *JWST*.

Acknowledgments: CAN was supported in this work by the NASA Astrobiology Institute (NAI) and Solar System Observing (SSO) Program.

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XANES ANALYSIS OF LABORATORY ANALOGS OF TITAN THOLINS.

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Introduction and Methods: The complex organic chemistry taking place in Titan's atmosphere between N_2 and CH_4 is induced by solar UV photons and energetic particles and results in the formation of a large variety of organic compounds, including hydrocarbons, nitriles, larger aromatic and heteroaromatic compounds, and aerosols that play an important role in its atmospheric dynamics, climate, and surface composition and processes [1]. Laboratory studies conducted in the past four decades showed that using various energy sources to induce dissociation and ionization of N_2 and CH_4 results in the formation of refractory organic materials (tholins) that are analogs of Titan's aerosols. These tholins have been studied with a wide variety of techniques to determine their compositions as well as their physical, chemical, and optical properties. Studies showed that tholins are macromolecular materials consisting mainly of carbon, nitrogen, and hydrogen, with a mixture of aliphatic and aromatic structures [2].

In this study, we produced laboratory tholins from gas mixtures of initial compositions N_2:CH_4 (90:10 and 95:5) and N_2:CH_4:C_2H_2 (89.5:10:0.5 and 94.5:5:0.5) using the Titan Haze Simulation (THS) experiment at the NASA Ames COSmIC facility [3,4]. A supersonic expansion is used to cool down gas mixtures to 150 K and to decrease the gas pressure to 30 mbar. A plasma discharge (–800 V) is then generated in the stream of that expansion to induce chemistry between the different molecular species present in the gas mixture. Larger species form in the gas phase and result in the formation of solid particles (tholins), analogs of Titan's aerosols, which can be collected for ex situ analyses.

Tholins were analyzed with a scanning transmission X-ray microscope (STXM) mounted on beamline 5.3.2.2 of the Advanced Light Source of the Lawrence Berkeley Laboratory [5]. X-ray absorption near-edge structure (XANES) spectra were measured in the carbon, nitrogen, and oxygen 1s X-ray absorption edge energy range (275–580 eV). XANES spectra provide information on the functional groups present and relative elemental abundances of C, N, and O [6,7], which allows for the determination of the C/N and C/O ratios.

Results: C-XANES spectra of all tholins show the presence of aromatic carbon (285.0–285.3 eV), imines (~285.9 eV), and nitriles (~286.8 eV), with relative proportions that vary widely from one sample to the other [8]. These bands are much more intense for tholins produced from mixtures containing C_2H_2, which is consistent with the fact that C_2H_2 is a known precursor of benzene. All C-XANES spectra also show bands associated with aliphatic carbon chains that are stronger for N_2:CH_4 (90:10), and multiple weak bands associated with amorphous carbon. N-XANES spectra of the 4 tholins are consistent with the C-XANES spectra and show more intense bands associated with nitriles and imines in tholin samples produced from mixtures that contain C_2H_2. The main bands observed in both C and N spectra of our N_2:CH_4 tholins are also consistent with those observed in a previous study for tholins produced in a different experimental set-up [9].

Elemental C/N ratios for the 4 tholins were determined to be 0.9–1.3 and 2.2–2.4 for tholins produced from gas mixtures in which C_2H_2 was absent and present, respectively [8]. The observation that C/N ratios are twice as large for tholins produced from C_2H_2-containing mixtures is correlated with the increase in aromatics, imines, and nitriles seen in these tholins. Further, higher concentrations of CH_4 (10% vs. 5%) result in smaller C/N ratios, suggesting that more N atoms are incorporated when mixtures contain more CH_4. For a given CH_4 concentration, adding C_2H_2 results in an increase of the C/N ratio, i.e., fewer N atoms are incorporated into the solid phase. Higher concentrations of CH_4 also result in more N-bearing bonds, while the presence of C_2H_2 may trigger a chemistry favoring the formation of hydrocarbons over that of N-bearing molecules, resulting in larger C/N ratios.

XANES spectra of all tholins also show O-bearing functional groups, despite the lack of O atoms in the starting gas mixtures. These may result from surface oxidation of the tholins, as they were produced as thin samples to allow X-rays to penetrate their full thickness. Oxidation was also observed in the XANES spectra of tholins produced from N_2:CH_4 (95:5) gas mixtures in an independent experimental set-up [9].

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QUANTIFYING THE RELATIVE INFLUENCE OF RIVER INCISION, WAVE EROSION, AND SCARP RETREAT ON TITAN'S SHORELINE MORPHOLOGY. Rose V. Palermo [1], J. Taylor Perron [2], Andrew D. Ashton[3], Jason M. Soderblom[2], Alexander G. Hayes [4], Samuel P. D. Birch [2], [1] MIT-WHOI Joint Program in Oceanography/Applied Ocean Science & Engineering (rpalermo@whoi.edu), [2] Department of Earth, Atmospheric & Planetary Sciences, Massachusetts Institute of Technology, [3] Department of Geology & Geophysics, Woods Hole Oceanographic Institution, [4] Department of Astronomy, Cornell University

Introduction: Titan's lakes and seas may record its climatic and geologic history. Titan's north polar landscape bears evidence of multiple surface processes, including river networks that flow into the seas [1,2,3], but the details of these processes and their relative influence on shaping the landscape remain unknown. Some have suggested that Titan's north polar lakes were created and shaped by dissolution [4,5], while the seas display evidence of mechanical erosion and sediment deposition [6]. Further, waves have possibly been observed [7] and models suggest that waves can form on Titan's seas [8].

We test the hypothesis that coastal erosion has shaped Titan's sea coasts. Using a combination of landscape evolution modeling and wavelet-based measurements of coastline morphology, we seek morphologic signatures that can distinguish wave-driven coastal erosion from scarp retreat or dissolution.

Landscape evolution model: We developed a landscape evolution model that simulates river incision, coastal erosion, and sea level change. River incision occurs as a function of slope and drainage area, carving valleys that roughen a landscape that subsequently becomes inundated during sea-level highstands [3]. Scarp retreat or dissolution is modeled as uniform (spatially invariant) coastal retreat, which generally smooths the coastline but generates cuspate points where promontories are eroded [9]. Wave-driven erosion occurs at a rate that depends on the fetch (the open-water distance wind and waves travel before reaching a point on the coast) and the angle between the shoreline and the wave crest [10, 11]. Wave-driven erosion tends to smooth stretches of open coast and preserve inherited roughness in protected embayments.

We simulate a highstand coastline that begins as an irregularly shaped, closed contour interrupted by flooded river valleys and evolves under the combined influence of wave erosion and uniform erosion. The shape of the resulting coastline reflects the relative influence of these two erosional processes, as measured by the ratio of their characteristic erosional timescales, τ_{wave} and $\tau_{uniform}$ (Fig. 1).

Quantifying coastline morphology: To fingerprint coastal erosion processes, we identify morphologic signatures in the simulation results that distinguish wave erosion from uniform erosion. Our approach to quantifying the shape of a closed coastline is based on the continuous wavelet transform [12]. We use the wavelet spectrum to obtain a localized measure of the variance of coastline orientation (a measure of roughness) at scales that are particularly sensitive to river incision or coastal erosion.

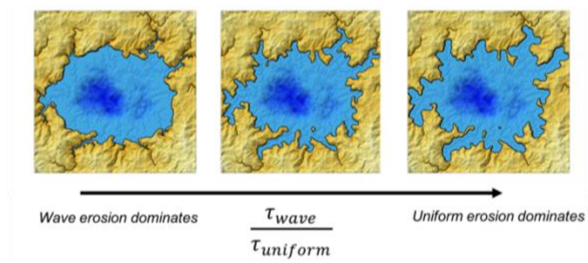

Figure 1: Model coastline shape records the relative influence of coastal erosional processes, as measured by a ratio of characteristic timescales (τ).

Comparing this roughness measure with fetch, we find a negative relationship for coastlines dominated by wave erosion (which smooths exposed parts of the coast but preserves roughness in embayments) and a positive relationship for coastlines dominated by uniform erosion (which tends to sharpen promontories but smooth embayments). We test this metric against shorelines on Earth with known coastal erosion mechanisms, and then apply it to sea coasts on Titan. Ligeia Mare shows a negative relationship between roughness and fetch, consistent with wave erosion.

Acknowledgments: This work was funded by the NASA Cassini Data Analysis Program (80NSSC18K1057) and National Science Foundation Graduate Research Fellowship Program (1745302).

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NEW RESULTS FROM THE AMES COSMIC AND OPTICAL CONSTANT FACILITIES: NEW OPTICAL CONSTANTS OF TITAN AEROSOL ANALOGS FROM VISIBLE TO MID-IR.

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Introduction: In Titan's atmospheres, the haze particles produced from the complex organic chemistry between nitrogen and methane play a major role. In particular, they can absorb and reflect light from UV to thermal infrared wavelengths, changing the atmospheric emission, reflection, and transmission spectra dramatically. Refractive indices are critical input parameters for radiative transfer models and other models used for the interpretation of observational data from Cassini and soon from Dragonfly and JWST. We have produced analogs of Titan aerosols (or tholins) in the Titan Haze Simulation (THS) experiment at Ames' COSmIC facility from N_2/CH_4 and $N_2/CH_4/C_2H_2$ mixtures, which previous studies[1] have proven to be the closest analogs to Titan's aerosols produced in the THS. Here we present the complex refractive indices of these two types of tholins from 0.4 to 20 µm.

Titan aerosol analog production with the COSmIC/THS: Titan aerosol analogs were produced in the COSmIC/THS, a unique experimental platform developed at NASA Ames that allows the simulation of Titan's complex atmospheric chemistry at Titan-like temperature[1,3]. COSmIC/THS uses a pulsed discharge nozzle (PDN) to generate a free supersonic jet expansion that cools down a N_2/CH_4-based gas mixture to Titan-like low temperature (150 K) before inducing the chemistry by plasma discharge. This results in the formation of larger, more complex molecules and eventually solid particles analogs of Titan's aerosols. In the study presented here, Titan tholins were produced from two gas mixtures to investigate the influence of the gas composition on the optical constants: N_2/CH_4 (95:5) and $N_2/CH_4/C_2H_2$ (94.5:5:0.5). Two additional solid samples were also produced from similar mixtures with argon instead of N_2, to assess the influence of nitrogen on the optical constants. The THS tholins were deposited on Si, KBr and diamond substrates, then their optical properties were characterized ex situ. Figure 1 shows a schematic of the PDN that is at the core of the COSmIC/THS and a picture of the plasma expansion during simultaneous deposition onto several substrates.

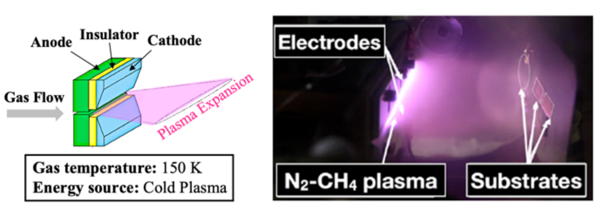

Figure 1. *Left*: schematic of the PDN. *Right*: photograph of the planar plasma expansion during tholin deposition.

Optical constant determination with the OCF: The real and imaginary refractive indices, *n* and *k*, were obtained with the recently developed Ames Optical Constant Facility (OCF). The core of the OCF is a Fourier transform infrared (FTIR) spectrometer that allows the continuous characterization of solid samples from the visible (Vis) to the far-infrared (FIR) (16,950–50 cm^{-1}, 0.59–200 µm) with high spectral resolution. Variable angle transmittance and reflectance accessories coupled to this FTIR spectrometer allow the characterization of the scattering properties of non-homogeneous samples over a wide incidence and emittance angle range (0-90 degrees). Analysis of the laboratory measurements conducted with the OCF will allow the determination of accurate optical constants, *n* and *k*, over the full Vis-FIR range.

We have measured the Vis to Mid-IR transmission spectrum of tholins produced from the gas mixtures described above and deposited on KBr windows. The same samples deposited on Si were characterized with spectral reflectance measurement by a commercial entity, Filmetrics, to measure the samples' thickness and determine their optical constants from 0.4 to 1.6 µm. As a first estimate, assuming a homogeneous film, we applied a simple Beer-Lambert calculation ($T=e^{-\alpha t}$) using an average Filmetrics-determined thickness (t) to get *k*-values, via $\alpha=4\pi k/\lambda$. Those *k*-values were then used in a subtractive Kramers-Kronig calculation, along with the Filmetrics *n*-value at 1.4 µm (a region of overlap between the two independent measurements), to determine the *n*-values. Calibrated reflectance and transmittance angle measurements have been conducted on the tholin deposited on diamond and more accurate *n* and *k* values calculations are under way.

These optical constants can be used as input parameters in radiative transfer, atmospheric and surface reflectance models, and are therefore critical in the analysis of observations returned from past and future space missions. Here we present the first of many invaluable measurements to be provided to the Titan community, thanks to the Ames COSmIC and Optical Constant Facility, for the interpretation of Titan observational data. Providing optical constants for various materials of different compositions will allow exploring a broad range of potential aerosol analogs.

Acknowledgments: This work is supported by directed funding (SERA, ISFM) from the NASA SMD Planetary Science Division.

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OPEN-SOURCE ANALYSIS OF TITAN'S RADAR-BRIGHT FLUVIAL FEATURES USING JMARS AND PYTHON. E. I. Serviss[1,2], D. M. Burr[2], and A. D. Maue[2], [1]University of Montana (32 Campus Dr, Missoula, MT 59812, eleanor.serviss@umontana.edu), [2]Northern Arizona University (S San Francisco St, Flagstaff, AZ 86011).

Introduction: Titan has over 60 radar-bright fluvial features that are several kilometers wide and over 50 kilometers long [1]. The high radar backscatter from these features in Cassini SAR data is interpreted to be wavelength-scale (~2.2 cm) rounded icy cobbles along the valley floor acting as retroreflectors [2]. Our study explores whether downstream changes in radar-brightness can indicate fluvial processes that alter the sediment properties of icy cobbles. Specifically, this study uses open-source technology (JMARS [3] and Python) to map and analyze these radar-bright features, building on and confirming previous analysis that used closed-source technology (ArcGIS) [1].

To collect data, these long, wide fluvial features are first mapped as elongated polygons. These polygons in turn are segmented into smaller polygons to track how characteristics, such as radar-brightness, change along the length of the valley. Because the two long edges of a fluvial feature have different lengths, the polygon's centerline measures the length of the feature and marks where to segment the polygon. We chose to segment the polygons every 5 km along their centerline so that the segments had enough pixels for statistical analysis.

Polygon-to-Centerline: ArcGIS has a built-in polygon-to-centerline tool and a tool to segment polygons along a line with a given distance. To create such a function using open-source software, we downloaded polygons mapped in JMARS as .csv or .shp shapefiles and processed those files in Python.

Because centerlines are frequently used in geospatial analysis, there are several algorithms that create them [4–8]. Our method uses Voronoi diagrams which are a common solution and are used in [4, 5]. Voronoi diagrams resemble irregular honey-combs with a single point (the "seed") in each cell. The cell walls consist of points that are closer to one seed than any other. In our case, the seeds are points on the border of the feature polygon and the cell walls trace out the centerline of the feature polygon.

In our method, we use SciPy Spatial's Voronoi package to quickly compute points that lie along the Voronoi cell walls. These points are transferred back to JMARS in a .csv shapefile. A user must manually draw a polyline in JMARS that goes through the centerline points (Fig. 1). Then this centerline is transferred back to Python to be marked every 5 km, and transferred again to JMARS for the user to segment the polygon where marked using JMARS's polygon intersect tool. Comparing these steps to ArcGIS's method, we find a ~1% difference in centerline length (Fig. 1).

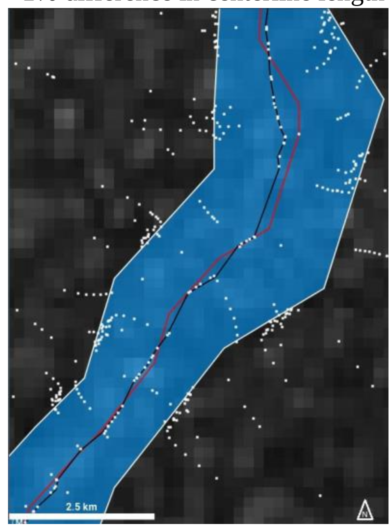

Fig. 1: Segment of polygon (blue) mapped in SAR from Cassini's T13, processed in ISIS3. Our centerline (black line) passes through Voronoi cell border points (white points). The ArcGIS centerline (red line) is 133.7 km vs our method's 132.1 km.

Conclusions: Overall, combining JMARS with Python opens a new range of geospatial analysis that can be done with open-source technology. Open-source methods are particularly useful for Titan where low-resolution data heavily relies on multiple mappers to constrain uncertainty. So far, we have mapped 12 of the 60 features using JMARS to compare to mapping done in ArcGIS. We will continue to map and analyze the rest of the 60 radar-bright fluvial features.

Future work will focus on making our centerline method more efficient. Combining our method with the branch-elimination code from [5] could eliminate the time it takes to draw the centerline's polyline and remove more human bias.

Our completed code will be freely available on GitHub in the "JMARS_with_Python" repository.

Acknowledgments: This work was funded by NSF through a Research Experience for Undergraduates at NAU. Cassini SAR swaths were obtained from the NASA Planetary Data System.

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Winter Weakening of Titan's Polar Vortices. J. Shultis[1], D. Waugh[1], A.D. Toigo[2], and C.E. Newman[3], [1]Johns Hopkins University, [2]Johns Hopkins Applied Physics Laboratory, [3]Aeolis Research

Polar vortices on Titan have been observed for many years, and our work analyzes the structure and time evolution of the polar vortices, using a combination of Cassini observations and results from the TitanWRF atmospheric model. The jet at the equatorward edge of the polar vortex is observed to lie between 60-30 degrees latitude in each hemisphere during its respective winter and exhibits a maximum velocity of ~200 m/s within the jet core at a pressure level of approximately 0.1 mb. Although Cassini observations have been a treasure trove of information about Titan's atmosphere, they are unfortunately limited to less than a full Titan year. Using TitanWRF model simulations of an entire Titan year to help fill in the spatial and temporal gaps of the observations, the polar vortex is found to have a non-monotonic variation in wind strength, temperature, and potential vorticity, and in particular we observe a noticeable minimum in the strength of the vortex at a time between winter solstice and spring equinox (around L_S=120° in the Southern hemisphere and L_S=310° in the northern hemisphere). An annular vortex is also observed to develop during this period of weakening. Analysis of the model results indicates that the formation of an annulus is linked to enhanced subsidence over the winter pole causing elevated heating and decreased potential vorticity within the vortex at those most poleward latitudes.

Magnetospheric O^+ Precipitation and Sputtering at Titan. D. S. Snowden[1], [1]Central Washington University, 400 E. University Way, Ellensburg, WA 98926

Introduction: Titan's dense and extended atmosphere is not protected by an internally generated magnetic field, exposing it to charged particle precipitation in Saturn's outer magnetosphere or, on occasion, the solar wind. Quantifying magnetospheric particle precipitation is important because the influx of ions affects the chemistry and structure of the atmosphere and the resulting sputtering contributes to atmospheric loss.

Magnetospheric O^+ precipitation is investigated using a three-dimensional Monte Carlo model of ion precipitation coupled to a multifluid model of Titan's interaction with Saturn's magnetosphere. It is necessary to model this process in three-dimensions and to consider Titan's interaction with Saturn's magnetosphere because Titan's induced magnetosphere partially shields the atmosphere, leading to precipitation rates that are spatially nonuniform. Sputtering rates also vary globally due to changes and asymmetries in the density of Titan's exosphere and atmosphere.

The sputtering rate of nitrogen is on the order of 10^{24} atoms s^{-1} [1], similar to the findings of pre-Cassini studies that assumed that primary ion in Saturn's magnetosphere near Titan was N_2^+. The model is used to investigate how the sputtering rate varies with fluctuations in Titan's upstream plasma environment, and atmospheric and exospheric density.

Previous models trying to explain the density of oxygen-bearing molecules in Titan's atmosphere assumed the number of O^+ entering the atmosphere is on the order of 10^6 cm^{-2} s^{-1} referred to the surface [2]. Our results suggested theses fluxes are about an order of magnitude too large, depending on Titan's plasma environment [1]. Again, we will investigate how the influx varies for a range of upstream parameters.

Finally, the model is used to investigate how sputtering and the flux magnetospheric O^+ varies over a Titan orbit, a solar cycle, and may have varied over the eons.

Acknowledgments:

Cassini MAG, INMS, and CAPS-IMS data sets were obtained from the Planetary Data System (PDS).

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Compositional Mapping for Titan's Surface

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Introduction: The investigation of Titan's surface chemical composition is of great importance for the understanding of the atmosphere-surface-interior system of the moon. The Cassini cameras and especially the Visual and infrared Mapping Spectrometer has provided a sequence of spectra showing the diversity of Titan's surface spectrum from flybys performed during the 13 years of Cassini's operation. Here, we investigate the spectral and emissivity behavior of Titan's surface by analyzing VIMS and RADAR data from various regions from all around the globe in order to constrain their composition.

Analysis: In the 0.8-5.2 μm range, the VIMS data contain information on both the atmosphere and the surface of Titan. Titan's extended, dense and hazy atmosphere, containing N_2 as well as CH_4 and aerosols, shields its surface from observation with VIMS. Therefore, studying Titan's surface requires very specific tools. We use a radiative transfer code built specifically for Titan [1-5]. Our plane-parallel code which is based on a SHDOMPP solver and includes Huygens inputs in addition to laboratory and theoretical data. This method has been used in various studies [1-8], in order to evaluate the atmospheric scattering and absorption and securely extract the surface albedo of multiple Titan areas including the major geomorphological units. We have also investigated the morphological and microwave characteristics of these features using Cassini RADAR data in their SAR and radiometry mode. Here, we present a global map for Titan's surface, showing the chemical composition constraints for the various units.

Results: The results show that Titan's surface composition, at the depths detected by VIMS, has significant latitudinal dependence, with its equator being dominated by organic materials, while higher latitudes contain more water ice (Fig. 1). We discuss our results in terms of origin and evolution theories.

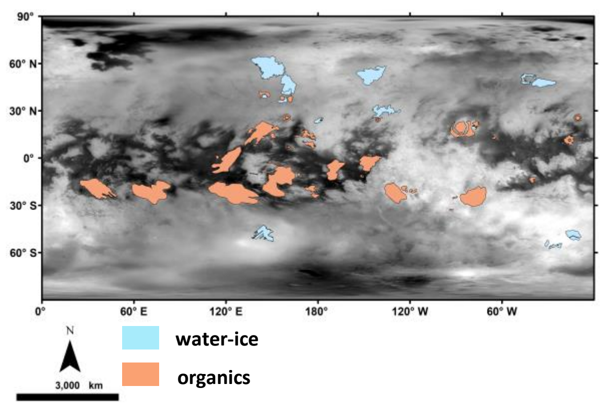

Figure 1: Preliminary compositional map of Titan's surface showing the organic and icy nature of major regions (VIMS basemap: LeMouelic et al. 2019).

Acknowledgments: This work was conducted at the California Institute of Technology (Caltech) under contract with NASA. ©2021 California Institute of Technology. Government sponsorship acknowledged.

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The Dragonfly Geophysics and Meteorology (DraGMet) Package: Exploring Titan's Atmospheric, Interior, and Surface Processes. K.S. Sotzen[1], R.D. Lorenz[1] and the DraGMet team, [1]Johns Hopkins University Applied Physics Laboratory (Ralph.Lorenz@jhuapl.edu; 11100 Johns Hopkins Rd, Laurel, MD 21074).

Introduction: Dragonfly is a relocatable lander that will arrive on Titan in the early 2030s. Capitalizing on Titan's low surface gravity and thick atmosphere, Dragonfly's rotorcraft design will allow it to explore diverse sites over dozens to hundreds of kilometers. Along with a camera suite, a mass spectrometer and a pneumatic surface sample acquisition system, and a gamma ray neutron spectrometer, Dragonfly will carry the Dragonfly Geophysics and Meteorology (DraGMet) instrument, which will take measurements of Titan's atmospheric, surface, and geophysical properties. DraGMet consists of a suite of simple sensor types along with dedicated power and data management electronics which will allow flexible data acquisition and processing. The collection of both meteorological and geophysical functions in a single package provides efficient implementation, and permits exact synchronization (e.g. of wind and seismic measurements).

Atmospheric Measurements: To observe Titan's meteorology, DraGMet will include sensors to measure wind speed and direction, temperature, methane and molecular hydrogen (H_2) abundance, and pressure. A microphone will also record sounds due to lander mechanisms and the environment. Temperature, pressure, methane, and hydrogen will be measured on the surface as well as during flights. There is particular scientific value in profiling the planetary boundary layer (PBL), so during transit between landing sites, Dragonfly will ascend to a cruising altitude of ~500 m, with a couple of dedicated altitude-profiling flights up to >3 km . Wind measurements will only be taken on the surface as readings during powered flight will be contaminated by perturbations from the rotors. While the other atmospheric measurements are of interest for meteorology, the hydrogen abundance is also of interest as an astrobiological measurement, as variations in the tropospheric H_2 mixing ratio may serve as a biomarker, depending on the implied consumption rate. The pressure, hydrogen, microphone, and temperature sensors are carefully-selected Commercial Off the Shelf (COTS) sensors, whereas the wind (thermal anemometer), and methane sensors are being designed and built by APL.

Geophysical Measurements: In addition to atmospheric observations, DraGMet will investigate Titan's surface and interior using a single vertical-axis seismometer and skid-mounted geophones (two sets) to measure seismic activity as well as antennas for electric field sensing of Schumann resonance possibly indicated by *Huygens* observations. The times of arrival of different seismic waves and the Schumann spectrum can each be used to constrain the depth to Titan's internal water-rich ocean. The Schumann electrodes may also respond to Aeolian sediment motion, if blown grains become triboelectrically charged. The seismometer is a contributed instrument from the Japanese Aerospace Exploration Agency (JAXA) and is lowered directly onto the ground by an APL-provided winch to minimize lander noise. The geophones are COTS sensors (of lower sensitivity than the seismometer, but able to operate in all axes, and immediately after landing), and the electric field antennas are being designed and built by APL. The installation of geophones on both skids will permit the determination of the regolith seismic velocity, using excitation from the sampling drills.

Surface Properties Measurements: DraGMet will also collect data on the properties of the surface material directly beneath the Lander. A pair of thermal properties sensors (one on each skid) will provide an indication of the methane moisture content of the regolith, which will inform the decision to drill for samples for the mass spectrometer. Other elements will permit derivation of the surface dielectric properties, constraining composition and porosity. Finally, a pair of photodiodes will detect sediment motion via shadowing during saltation experiments, wherein a rotor will be powered to apply wind stress on the ground. These sensors can also detect cloud acitivity and measure light scattering by Titan's haze.

Conclusion: The comprehensive suite of individually-simple measurements by DraGMet will together greatly expand our in situ observations of the Titan environment, offering new insights into an ocean world where we hope to find evidence of prebiotic – and just possibly biological – processes.

Exploring Titan's atmospheric turbulence with Large-Eddy Simulations

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Context One key element of the dynamic Titan's atmosphere[1] is the Planetary Boundary Layer (PBL), defined as the lowermost part of the atmosphere directly influenced by the presence of a surface below it. Turbulence in the PBL is a controlling factor for exchanges of momentum, heat, chemical species and aerosols between surface and atmosphere. Studying Titan's PBL dynamics is a means to progress on the understanding of its near-surface weather events, from methane storms[2] to possible dust-lifting events, and their link to the volatile and aerosol cycles in Titan's atmosphere. Furthermore, basic knowledge on PBL turbulence on Titan is needed in the perspective of the Dragonfly mission arriving in the mid-2030s over Titan's equatorial dune field of Shangri-La[3].

Methods Atmospheric models are usually composed of two parts coupled together in a time-marching integration of differential equations. On the one hand, the "dynamical core" is a hydrodynamical solver in charge of solving the Navier-Stokes equations governing the evolution of the atmospheric flow. On the other hand, the "physical parameterizations" are a set of parametric models, each relying on equations ranging from idealized to sophisticated, to represent the phenomena not resolved by the dynamical core (e.g., radiative transfer, soil model). The model we used here to perform high-resolution turbulence-resolving Titan Large-Eddy Simulations [LES] couples the dynamical core extracted from the Weather Research and Forecast (WRF) terrestrial model with the Titan physical parameterizations developed for the Titan Global Climate Model (GCM)[4], akin to projects on Mars[5] and Venus[6].

Results Our Titan LES shows that, for conditions close to the Huygens landing site, daytime turbulence is characterized by buoyant plumes reaching an altitude of 1 km above the surface, compliant with GCM studies in which PBL mixing is parameterized[7]. The typical vertical velocity of those plumes (updraft and downdraft) is 0.2 m s^{-1}; plumes are organized horizontally as polygonal convective cells. Horizontal wind gusts associated with this convective turbulence reach maximum values of 0.05 m s^{-1}. At the intersection of convective cells, low-pressure vortical phenomena of amplitude -250 mPa develops naturally in our Titan LES – raising the possibility of dust devils on Titan should dusty material on the surface be lifted and transported in those convective vortices.

Perspectives The results presented here uses LES with prescribed sensible heat flux. A full coupling with the diurnal cycle of near-surface conditions computed by the Titan LMD physics is being implemented at the time of writing.

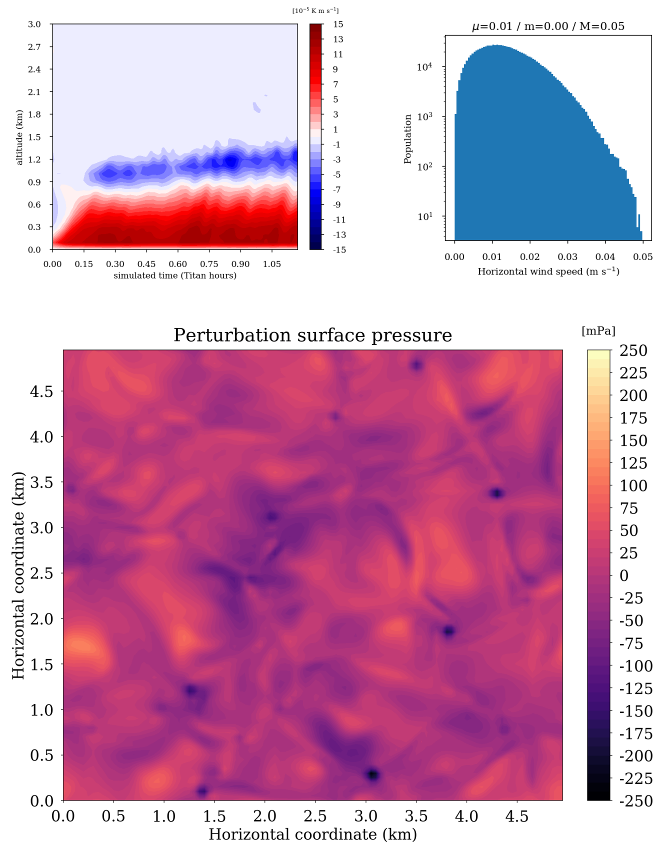

Figure 1: ***Results from the LMD Titan LES****: [top left] temporal evolution of vertical eddy heat flux [top right] histogram of near-surface wind speeds [bottom] map of perturbation pressure.*

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TITAN'S CLIMATE CYCLE.

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Introduction: Titan hosts a dynamic hydrologic cycle that currently includes stable lakes of predominantly methane on its surface [1–3], and atmospheric methane that drives a greenhouse effect [4,5] sufficient to keep the surface and atmosphere near methane's triple point temperature. This methane-driven hydrologic cycle is short-lived, in geologic terms, due to relatively rapid photo-destruction, which will remove Titan's current methane inventory from its climate system in a few 10's if million years [6]. Without sufficient atmospheric methane to drive a methane greenhouse, Titan's surface temperatures would plunge to ~80K or below [4,5]. Such conditions would cause Titan's atmosphere to partially collapse, forming a global-scale nitrogen ocean [4,5].

Here we show that, in this frigid "Slushball" climate state, any methane released into Titan's climate system would dissolve into the global nitrogen ocean. This deprives the atmosphere of a methane greenhouse effect, which stabilizes this slushball climate. Furthermore, methane sequestration and photodissociation cause Titan to naturally cycle between a Slushball climate and Titan's current "Warm" climate state.

Methods: We use our TITANPOOL code [7] to model the composition of Titan's surface liquids and atmosphere as they transition between climactic regimes. TITANPOOL computes the equilibrium partition of chemical species into liquid and gas phases on Titan [7], from which we compute the surface pressure and composition of the atmosphere and surface liquids as a function of surface temperature. We use TITANPOOL to explore the conditions of the two climate regimes, and compare these surface conditions to the methane partial pressure required to drive a methane greenhouse effect (~0.01 bar [4]).

Results: We find that the amount of methane in the atmosphere depends sensitively to both surface temperature and climate system composition. Thus, the temperature at which the climate transitions between these two climate states depends on the amount of methane in the climate system. At Titan's current composition, the tipping-point temperature between these two regimes occurs around ~80K. However, as photodestruction removes methane from the system, this tipping-point temperature shifts warmer. If Titan had only ~20% of its current methane, this tipping-point temperature is around ~82K. Eventually, insufficient methane exists to maintain a Warm climate at any temperature, and Titan collapses into its Slushball state.

This behavior naturally leads to cyclical behavior in Titan's climate so long as there is a steady supply of methane into Titan's surface–atmosphere system. In the Slushball state, any methane released into the climate system from Titan's interior will preferentially dissolve into the nitrogen ocean, keeping Titan's atmosphere relatively methane-free. However, as the ocean saturates, additional methane will build up in the atmosphere and eventually reestablish a methane greenhouse effect. This will cause the surface to rapidly warm, largely evaporating the nitrogen ocean and expelling its dissolved methane into Titan's atmosphere. This process rapidly transitions Titan into the Warm climate regime, where photo-destruction can eventually drive Titan back into the slushball state, starting the cycle anew.

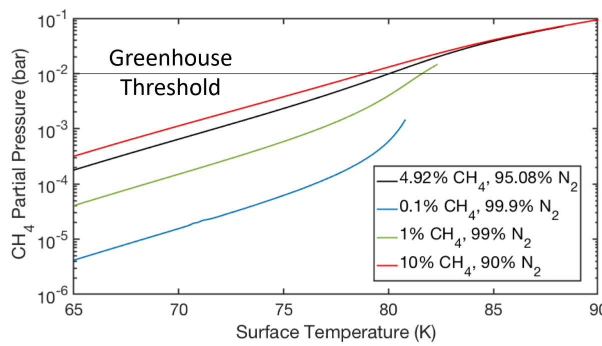

Figure 1: Equilibrium surface partial pressure of Titan's methane, as a function temperature and molar composition of Titan's climate system (N_2 and CH_4). N_2 quantity assumed to always match current Titan.

Conclusions: Titan's climate is controlled by the presence/absence of an atmospheric methane greenhouse effect. Because of the unique thermodynamic interactions of liquid nitrogen and liquid methane at the surface and the photo-dissociation of atmospheric methane, slow releases of methane can cause Titan's climate to naturally cycle between Slushball Titan and Warm Titan climate states.

Acknowledgments: This work was supported by NASA awards NNX15AL48G and 80NSSC18K0967.

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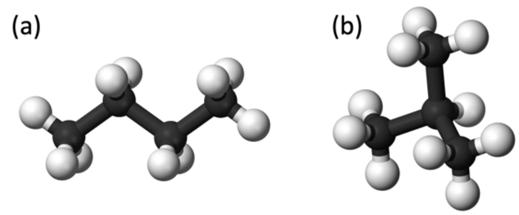
THE ONGOING SEARCH FOR TITAN'S N-BUTANE. B.L. Steffens[1] and C.A. Nixon[2] and K. Sung[3] and P.G.J. Irwin[4] and N.A. Lombardo[5] and E. Pereira.[1] [1]Florida Institute of Technology, 150 W University Blvd, Melbourne, FL 32901. [2]NASA Goddard Space Flight Center, Planetary Systems Laboratory, Code 693, Greenbelt, MD 20771. [3]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109. [4]Department of Physics, University of Oxford, Oxford OX1 2JD, UK. [5]Yale University, New Haven, CT, USA.

Introduction: The C_4 chemistry of Titan's atmosphere, while important for its photochemical modeling, is currently poorly constrained. One of the primary C_4 hydrocarbons expected to be present is *n*-butane (*n*-C_4H_{10}: CH_3-CH_2-CH_2-CH_3). Though its predicted abundances span more than two orders of magnitude, from 1 ppb[1] to hundreds of ppb[2-3], it has yet to be detected there by any means.



Butane comes in two spectroscopically distinct isomers, as seen above, with the first being *n*-butane (a) and the other being isobutane, (b) $HC(CH_3)_3$, both of which are likely to be present on Titan. As isobutane's abundance has already been explored and preliminary constraints on its abundance have been established,[4] and due to the availability of a newly derived, high-resolution pseudoline list for *n*-butane,[5] our search has been focused on the latter of the two isomers. We note also that laboratory simulations of Titan's atmospheric conditions suggest that production of *n*-butane is favored over that of isobutane, and we therefore expect *n*-butane to be more abundant and more readily detectable.[6]

Motivation: Detecting or constraining the abundance of this important molecule would constitute a significant step forward in the investigation of Titan's C_4 chemistry. Additionally, butane molecules are thought to be a significant trace constituent of Titan's lakes and seas.[7] Constraining the atmospheric abundance of butane may therefore lead to improved understanding of these features which render Titan such a unique planetary body of our solar system. It is also expected that butane (and other, larger molecules) play a role in the nucleation of Titan's hazes, which are currently poorly understood.[8]

Methodology: We searched for *n*-butane signals in three sets of observations collected by Cassini's CIRS (Composite Infrared Spectrometer) instrument.[9] The data were obtained via CIRS Focal Plane 4 (FP4), covering the spectral range 1100-1500 cm^{-1}. Each of the three data sets were derived from different Titan flybys[10] and different latitudes, with one set targeting equatorial latitudes,[11] and the others targeting Titan's north pole.

We modeled these observations using the **N**onlinear Optimal **E**stimator for **M**ultivariat**E** Spectral Analy**SIS** planetary atmosphere radiative transfer and retrieval tool.[12] We began with retrieving temperature profiles by modeling methane's ν_4 emission at 1305 cm^{-1}. We then fixed the retrieved temperature profiles in place and modeled the 1300-1500 cm^{-1} region, primarily targeting *n*-butane's strong ν_{32} and ν_{14} bands near 1383 and 1466 cm^{-1}, respectively, retrieving abundances for Titan's other gases in the process. We searched for evidence of the *n*-butane bands in the residuals between our model and the observations.

Results: Though we do not see explicit *n*-butane signals in our results, we are able to show that in some cases, particularly for the T3 flyby (latitude 82 degrees north) data in altitude range 162-272 km, statistically significant improvement (as large as 3.88σ) to our model's fit occurs when *n*-butane is added to the model in abundances consistent with previous upper limits in the literature.[4] Though this certainly does not constitute a firm detection of *n*-butane, we interpret it as strong evidence for this gas's presence and detectability via future, higher resolution observations. We were also able to derive a comprehensive set of upper limits on *n*-butane's abundance at different altitudes, using three different photochemically predicted profiles.[1-3] These upper limits can be implemented in future photochemical modeling of Titan's atmosphere.

Acknowledgments: We would like to acknowledge the Planetary Data System which we used to obtain our observations. Part of the research carried out at the Jet Propulsion Laboratory was funded through contracts and co-operative agreements from the National Aeronautics and Space Administration.

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MODELING CAPILLARY CONDENSATION OF TITAN'S FLUIDS IN SMALL PORES. S. P. Tan[1], [1]Planetary Science Institute, Tucson, AZ, U.S.A. (stan@psi.edu).

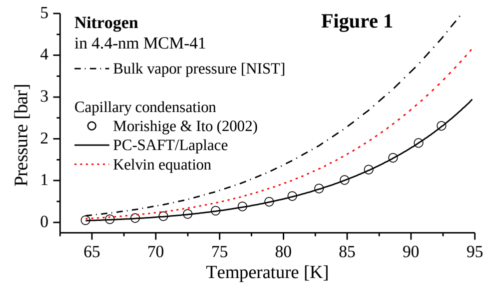
Introduction: It is well known that fluids behave differently compared to their bulk if confined in small pores, including their phase behavior [1]. They condense at bulk pressures lower than their vapor pressures. The pressure drop is larger for smaller pores; it can be more than half of the bulk vapor pressure for mesopores with nm-size as shown in Figure 1 for nitrogen in 4.4-nm silica pores. The conventional Kelvin equation fails as it overestimates experimental data.

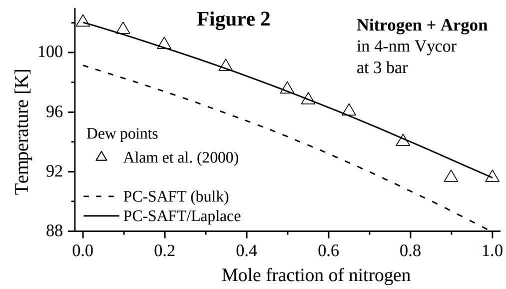
The physics behind the drop is that the attractive wall-fluid interaction inside the pores is so strong that the condensed liquid is under stretching tension (negative pressure) instead of compressing pressure as that in the bulk outside the pores. The large pressure difference between fluids inside and outside the pores is known as capillary pressure, and the transition to liquid inside the pores is termed as capillary condensation.

The capillary phenomena have great impacts on subsurface fluids, such as oil and natural gas on Earth. The capillary pressure holds the hydrocarbons inside the pores of rock formation and must be overcome before they are recoverable to the surface. The smaller the pores are, such as in tight shale formations, the stronger the capillary pressures are to overcome in the recovery. On the other hand, the capillary condensation has been known to cause underestimation of original gas in place, because conventional estimation does not include the condensed phase in pores.

By comparison, calculated composition of Titan's surface liquid [2] is similar to that of Earth natural gas. The liquid may flow down through fractures or crusts with large pores, then stay underground as part of the alkanology analogous to terrestrial hydrology [3,4]. If the warmer condition in the deep allows the liquid to become gaseous [5], while the crust has smaller pores due to compaction, capillary condensation may occur when the gas is trapped inside pores then subsequently seals the space beneath them. It is similar to the situation in sealed hydrocarbon reservoirs on Earth. Unless the seal fails, the fluid will stay in the reservoir. The failure can be due to overpressure from beneath that overcomes the capillary pressure. When this happens, the fluid escapes from the reservoir to the surface, such as that with natural oil seeps on Earth, where oil and natural gas flow slowly through network of cracks to the surface [6]. These seeps can be a potential mechanism that spreads widely on the surface and occurs very slowly, which facilitate the need for continuous supply of methane to Titan's atmosphere to prevent depletion. Moreover, as found on Earth, hydrocarbon seeps support diverse biological activities [7], thus relevant to research of finding extraterrestrial life.

It is, therefore, of interest in this work to investigate the magnitude of capillary pressure of Titan's fluid. The results in turn would allow better models in future works on the fate of Titan's subsurface fluids along with their potential to harbor some life forms.





Modeling: An equation of state that can calculate capillary condensation and the corresponding capillary pressure in nanosize pores is used (PC-SAFT/Laplace [8]). Its performance for pure gas is shown in Figure 1, while for mixtures is shown in Figure 2.

Titan's fluids. Because the work is aimed to provide a first approximation of the magnitude of capillary pressure, a simplified fluid composition as a ternary mixture of nitrogen/methane/ethane is applied [9].

Acknowledgments: This work was funded by NASA Astrobiology Institute Grant 17-NAI8_2-0017.

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Mesospheric Temperatures and HCN Abundances in Titan's Northern Spring. A. E. Thelen[1,2], C. A. Nixon[1], M. A. Cordiner[1,3], R. Cosentino[4], P. G. J. Irwin[5], S. B. Charnley[1]. [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA, [2]Universities Space Research Association, Columbia, MD 21046, USA, [3]Institute for Astrophysics and Computational Sciences, The Catholic University of America, Washington, DC 20064, USA, [4]Space Telescope Science Institute, Baltimore, MD 21218, USA, [5]Atmospheric, Oceanic and Planetary Physics, Clarendon Laboratory, University of Oxford, Oxford, OX1 3PU, UK.

Introduction: The complex nature of Titan's upper atmospheric dynamical state (altitudes >600 km) was revealed by measurements from the Ion and Neutral Mass Spectrometer and Ultraviolet Imaging Spectrometer instruments onboard the Cassini spacecraft [1, 2]. These studies observed large changes in mesospheric and thermospheric temperature profiles, thought to be the result of variable wave activity, EUV heating, magnetospheric interactions, and the distribution of Titan's minor atmospheric constituents.

Interferometric observations by the Atacama Large Millimeter/submillimeter Array (ALMA) provide an additional means by which to study variability in Titan's upper atmosphere. We analyzed ALMA archival observations acquired between 2012 and 2017 to investigate changes in Titan's atmospheric temperature profile by utilizing strong rotational emission lines of carbon monoxide (CO) and hydrogen cyanide (HCN). Models of CO emission allowed for the derivation of Titan's stratospheric temperature profile while holding the CO mixing ratio constant at ~50 ppm [3, 4]. Titan's mesospheric temperatures were then measured through the simultaneous retrieval of thermal and HCN abundance profiles [5].

Here, we compare mesospheric temperature and HCN mixing ratio profiles at low northern latitudes (~20º N) from yearly ALMA observations starting in 2012 leading to Titan's northern summer solstice in 2017. Measurements derived from ALMA data show variability in the altitude and temperature of Titan's mesopause during northern spring. Thermal and HCN mixing ratio profiles throughout Titan's middle and upper atmosphere by ALMA complement and further contextualize data obtained during Cassini's extended mission, and provide constraints for dynamical and circulation models. This work also further validates the use of ground-based (sub)millimeter facilities for the continued monitoring of Titan's seasonal evolution during the post-Cassini era.

Acknowledgments: Support for this research was provided by the NASA Astrobiology Institute and Solar System Observations program, the National Science Foundation, and the UK Science and Technology Facilities Council. This paper makes use of the following ALMA data: ADS/ JAO.ALMA#2011.0.00727.S, 2011.0.00820.S, 2012.1.00133.S, 2012.1.00635.S, 2012.1.00453.S, 2013.00233.S, 2012.1.00278.S, 2013.1.00446.S, 2015.1.00777.S, 2015.1.01023.S, 2015.1.01599.S, 2016.1.00829.S, 2016.A.00014.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan) and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/ NRAO, and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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DEVELOPMENT OF THE *DRAGONFLY* MASS SPECTROMETER (DRAMS) FOR TITAN. M. G. Trainer[1], W. B. Brinckerhoff[1], A. Grubisic[1], R. M. Danell[1,2], D. Kaplan[1,3], F. H. W. van Amerom[1,4], X. Li[1,5], C. Freissinet[6], C. Szopa[6], A. Buch[7], J. C. Stern[1], S. Teinturier[1,8], C. A. Malespin[1], P. W. Barfknecht[1], P. R. Stysley[1], D. B. Coyle[1], M. W. Mullin[1], B. L. James[1], E. I. Lyness[1,9], R. S. Wilkinson[1,10], J. W. Kellogg[1], K. Zacny[9], D. C. Wegel[1], E. P. Turtle[10], and the *Dragonfly* Team. [1]NASA Goddard Space Flight Center, Greenbelt MD (melissa.trainer@nasa.gov), [2]Danell Consulting, Winterville NC, [3]Kapscience, Tewksbury MA, [1,4]Mini-Mass Consulting, Hyattsville MD, [5]University of Maryland Baltimore County, Baltimore MD, [6]LATMOS, Guyancourt, France, [7]LPGM, Gif-sur-Yvette, France, [8]Universities Space Research Association, Columbia MD, [9]Microtel, Greenbelt MD, [10]ATA Aerospace, Greenbelt MD, [11]Honeybee Robotics, Altadena CA, [12]Johns Hopkins University Applied Physics Laboratory, Columbia MD.

Introduction: Titan's abundant complex carbon-rich chemistry, interior ocean, and past presence of liquid water on the surface make it an ideal destination to study prebiotic chemical processes and habitability of an extraterrestrial environment [*e.g.*, 1-4]. NASA's *Dragonfly* New Frontiers mission is a rotorcraft lander [5] designed to perform wide-ranging *in situ* exploration on this moon of Saturn by flying to different geologic settings up to ~180 km apart. Multidisciplinary science measurements at each landing site will reveal the compositions of the solid materials on Titan's surface, which are still essentially unknown [6-8].

Two primary science goals of the *Dragonfly* mission are to identify chemical components and processes at work that may produce biologically relevant compounds, and to search for potential molecular biosignatures. These objectives are addressed by the *Dragonfly* Mass Spectrometer (DraMS), which performs molecular analysis on surface samples that are acquired and delivered by the Drill for Acquisition of Complex Organics (DrACO).

The *Dragonfly* Mass Spectrometer (DraMS): DraMS is a linear ion trap mass spectrometer, most closely related to the Mars Organic Molecule Analyzer (MOMA) [9], part of the ExoMars *Rosalind Franklin* Rover set to launch in 2022. For solid sample analysis, DraMS features two modes: Laser Desorption Mass Spectrometry (LDMS) for the broad compositional survey of surface materials including refractory organics, and Gas Chromatography Mass Spectrometry (GCMS) for the separation and identification of key prebiotic molecules and measurement of enantiomeric excesses (if present). LDMS mode allows for structural disambiguation of surface molecules using ion isolation and tandem mass spectrometry (MS/MS). GCMS mode uses pyrolysis or derivatization to volatilize, separate, and identify molecules of interest. Much of the gas processing system (valves, pyrolysis oven, etc.) and electronics are also inherited from the Sample Analysis at Mars (SAM) instrument onboard *Curiosity* [10].

Hardware Developments: *Dragonfly* was selected by NASA in June 2019, and technical development activities related to DraMS through the first part of Phase B have focused on areas in which the unique aspects of the Titan environment and *Dragonfly* science [11] differed from the heritage Mars instruments.

These areas of focus include: (1) the interface between the DrACO sampling system and the LDMS and GCMS inlets to the mass spectrometer; (2) thermal control of the Titan surface samples during analysis; (3) the ultraviolet (UV) laser technology maturation to support LDMS mode; (4) the pumping system used to operate at Titan's surface pressure; (5) improved performance metrics as compared to the MOMA-MS instrument; and (6) required operational parameters of GCMS, including pyrolysis and derivatization, to accommodate the potential range of abundances and compositions in the samples.

Acknowledgments: *Dragonfly* and DraMS development is currently supported by the NASA New Frontiers program. The GC module for DraMS is being developed in partnership with the French Centre National d'Études Spatiales (CNES).

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DRAGONFLY: IN SITU EXPLORATION OF TITAN'S ORGANIC CHEMISTRY AND HABITABILITY.

E. P. Turtle[1], M. G. Trainer[2], J. W. Barnes[3], R. D. Lorenz[1], K. E. Hibbard[1], D. S. Adams[1], P. Bedini[1], W. B. Brinckerhoff[2], M. T. Burks[4], M. L. Cable[5], C. Ernst[1], C. Freissinet[6], K. Hand[5], A. G. Hayes[7], S. M. Hörst[8], J. R. Johnson[1], E. Karkoschka[9], J. W. Langelaan[10], D. J. Lawrence[1], A. Le Gall[6], J. M. Lora[11], S. M. MacKenzie[1], C. P. McKay[12], R. S. Miller[1], S. Murchie[1], C. D. Neish[13], C. E. Newman[14], J. I. Núñez[1], J. Palacios[10], M. P. Panning[5], A. M. Parsons[2], P. N. Peplowski[1], L. C. Quick[2], J. Radebaugh[16], S. C. R. Rafkin[17], M. A. Ravine[18], S. Schmitz[10], H. Shiraishi[19], J. M. Soderblom[20], K. S. Sotzen[1], A. M. Stickle[1], E. R. Stofan[15], C. Szopa[6], T. Tokano[21], C. Wilson[22], R. A. Yingst[13], K. Zacny[23], [1]JHU/APL, Laurel, MD (Elizabeth.Turtle@jhuapl.edu), [2]NASA GSFC, Greenbelt, MD, [3]Univ. Idaho, Moscow, ID, [4]LLNL, Livermore, CA, [5]JPL, Pasadena, CA, [6]LATMOS, Guyancourt, France, [7]Cornell Univ., Ithaca, NY, [8]Johns Hopkins Univ., Baltimore, MD, [9]Univ. Arizona, Tucson, AZ, [10]Penn State Univ., PA, [11]Yale Univ., New Haven, CT, [12]NASA ARC, Moffett Field, CA, [13]PSI, Tucson, AZ, [14]Aeolis Research, Pasadena, CA, [15]Smithsonian Inst., DC, [16]Brigham Young Univ., Provo, UT, [17]SWRI, Boulder, CO, [18]MSSS, San Diego, CA, [19]JAXA ISAS, Japan, [20]MIT, Cambridge, MA, [21]Univ. Cologne, Germany, [22]Oxford Univ., UK, [23]Honeybee Robotics, Pasadena, CA.

Introduction: Titan's abundant complex carbon-rich chemistry, interior ocean, and past presence of liquid water on the surface make it an ideal destination to study prebiotic chemical processes and document the habitability of an extraterrestrial environment [*e.g.*, 1-6]. Although pathways for the origin of life-as-we-know-it are poorly constrained, there is general agreement that liquid water, essential elements (especially CHNOPS), energetic disequilibrium, and a catalytic surface are required. In addition to the complex organic synthesis occurring on Titan today, organic molecules may have interacted with liquid water at the surface in the past [4], increasing the potential for oxygenation and chemical processing to progress beyond the compositional functionalities observed in high-altitude organic species. Titan provides an unparalleled opportunity to investigate prebiotic chemistry, and search for signatures indicative of biological processes.

Titan's dense atmosphere (4x Earth's) and low gravity (1/7th Earth's) make heavier-than-air flight highly efficient [*e.g.,* 7-9], and recent development in autonomous flight enables a lander with aerial mobility to achieve long-range exploration. The *Dragonfly* rotorcraft lander [10], scheduled to launch in 2027 and arrive at Titan in the mid-2030s, will perform wide-ranging *in situ* exploration to sample diverse surface materials in a variety of geologic environments [11].

Landing Site and Exploration Strategy: *Dragonfly's* initial landing site lies within Titan's equatorial longitudinal dunes to the south of Selk Crater [12]. The dunes and interdunes provide access to multiple types of materials in close proximity, including organic sediments and materials with a water-ice component [13]. Over ~3.3 years (74 Tsols), *Dragonfly* will perform a series of flights covering several kilometers each, ultimately traversing up to ~180 km to investigate deposits associated with the 80-km-diameter impact crater. Using a "leapfrog" exploration strategy, *Dragonfly* will scout and select potential landing sites in advance based on aerial observations. Sites where liquid water may have interacted with the photochemical products that litter the surface are of particular interest [4].

Science Objectives: Compositions of solid materials on Titan's surface are still essentially unknown. Measurements of samples from different locations will reveal how far organic chemistry has progressed [14]. Along its traverse, *Dragonfly* will make multidisciplinary science measurements at up to ~30 unique sites to provide context of Titan's meteorology and methane cycle, local geology and material properties, and geophysical measurements of the subsurface [15-19].

Student and Early Career Investigator Program: The *Dragonfly* team is dedicated to broadening participation on planetary mission teams and providing experience to the next generation of planetary scientists and engineers. The Guest Investigator Program [20] aims to serve as an on-ramp for students from a variety of STEM fields, and the initial phase provides opportunities to support mission and instrument development. The program is beginning its second year, and will extend through surface operations at Titan.

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The thermodynamics of Titan's abysses, Part II:
Using a new water ammonia equation of state to model the structure of Titan's hydrosphere

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Introduction: The radial structure of Titan's interior remains a mystery. The inventory of volatiles in its atmosphere suggests the production of methane and ammonia in the interior from the breakdown of organic materials [1,2], which would supply further species to the ocean's equilibrium composition of dissolved ions such as Na^+ and Cl^- [3]. Because of the strong melting point suppression of dissolved ammonia, it is important to account for the influence of ammonia in Titan's ocean. In this work, we will make use of recent progress in measuring the thermodynamics of the H_2O-NH_3 system to explore the potential effects on Titan's ocean. This work is part of a larger effort to develop a systematic equation of state for multicomponent aqueous systems covering the range of pressures and temperatures relevant to ocean worlds.

Models: We construct radial structure models using the PlanetProfile framework [4]. Models use updated silicate properties matching the composition of comet 67P [5]. It must be emphasized that the present models do not meet the low silicate densities required by Cassini gravity data [2]. However, this discrepancy does not affect the precise gravity and corresponding layer thicknesses computed in the hydrosphere, which is the main focus of this work. We apply the SeaFreeze framework for the water-ice system, which makes use of a local basis function approach to developing self-consistent equations of state [6,7]. To this framework we add the new equation of state (EoS) for water-ammonia solutions developed by Journaux et al. (this meeting).

We will examine hypothetical Titan oceans containing only aqueous ammonia in concentrations of 0, 3, and 7 wt%. Pure water and 3 wt% ammonia oceans were previously considered [4]. It is useful to compare the new results with those previous models, which used entirely different equations of state for all materials. The same basal temperatures of the ice shell T_b were assumed for the new models, {250,265,268}K and {250,260,264}K respectively. For the 7wt% case we consider T_b={255, 260}K. These values correspond to ice thicknesses in the range 50-150 km.

Results: The improved thermodynamic data reveal that high pressure ices should only be present at the base of Titan's ocean if the overlying ice shell is thicker than 100 km. Only the lowest temperature models in Figure 1 show the presence of high-pressure ice V and VI. All other models have oceans in direct contact with the seafloor.

Even small amounts of ammonia have important effects on Titan's ocean. Each. ~3 wt% addition of ammonia lowers the ocean's temperature by about 5K for comparable thicknesses of ice. Because of the high compressibility of water in the range of pressures in Titan's hydrosphere, the mean densities of the model oceans are high, around {1100,1075} kg/m^3, despite the positive partial molal volume of ammonia. We will describe these findings in further detail, including the effects on the expected sound speeds in Titan's ocean.

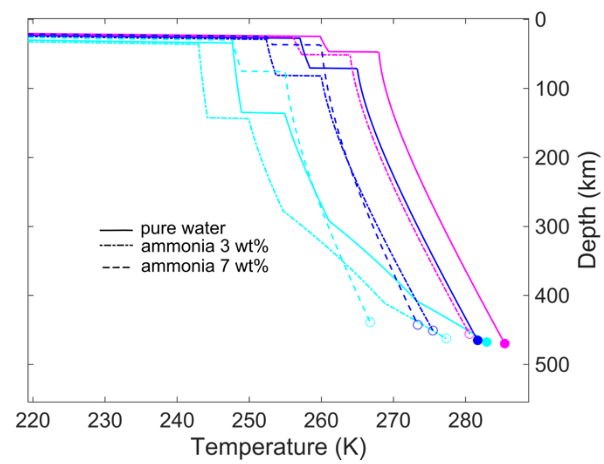

Figure 1: Geotherms for Titan oceans containing water (solid lines) and 3 and 7 wt% dissolved ammonia (dash-dot and dashed lines). Only ice shells thicker than 100 km have high-pressure ice layers. Colors group the relative basal temperatures for each composition: lowest (cyan), medium (blue), highest (magenta).

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THE EFFECTS OF A METHANE-SATURATED LAYER ON THE MORPHOLOGY OF IMPACT CRATERS ON TITAN. S. Wakita[1,2*], B. C. Johnson[1,3], J. M. Soderblom[2], J. Shah[4], and C. D. Neish[4], [1]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, USA, [2]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [3]Department of Physics and Astronomy, Purdue University, West Lafayette, IN, USA, [4]Department of Earth Sciences, The University of Western Ontario, London, ON, Canada (*shigeru@mit.edu).

Introduction: Cassini observations reveal a variety of craters on Titan in terms of size, morphology, and location [1,2]. Titan craters are preferentially located at high-elevation regions; hypotheses to explain this are the presence of wetlands or a former global ocean in low-elevation regions [3]. Previous work has shown that fluid-saturated sediment can weaken the target and limit the topographic expression of impact craters [4], resulting in craters that may be difficult to detect from orbital remote sensing observations. Here we simulate impacts on Titan and confirm that a methane-saturated layer can produce craters with limited topographic expression.

Methods: To simulate impacts into Titan, we use the iSALE-2D shock physics code [5-7]. We assume a spherical icy body vertically impacting a flat layered target and consider impactors that range from 1 km to 5 km in diameter with an impact velocity of 10.5 km/s [8]. We consider two materials in the target: methane-clathrate ice and methane-saturated icy regolith. Experimental work shows that methane clathrate is 20–30 times stronger than water-ice [9]; we adopt a limiting strength of methane clathrate as 20 times stronger than that of water ice. We model the methane-saturated layer as a weak water-ice layer, based on the rheology of water-saturated sediments used in terrestrial impact simulations [4]. For all icy materials, we use the Tillotson equation of state for water ice [10]. To investigate the role of the methane-saturated layer, we consider a range of thickness from 0 km to 5 km on the top of methane clathrate crust.

Results: The methane-saturated layer limits the topographic expression of the impact crater. Figure 1 summarizes the depth and diameter of the resultant cavities. When the methane-saturated layer is thin (less than 25% of the impactor diameter; square symbols in Figure 1), the impact crater cavities are preserved. However, they are smaller and shallower than comparable impacts into a target without a methane-saturated layer (circle symbols in Figure 1). For cases when the methane-saturated layer is thicker (more than 40% of the impactor diameter; cross symbols in Figure 1), the crater cavity becomes infilled with weak sediment. These crater morphologies would be hard to detect by remote sensing techniques, so a thick methane-saturated layer is promising to explain the dearth of lowland craters on Titan [3].

We also found that the morphology of craters depends on the thickness of the methane-saturated layer. While craters formed in a methane-clathrate target have clear rims, cavities formed in targets with even a thin methane-saturated layer exhibit no rims. Our results imply that the craters with rims are likely formed in a target without a methane-saturated layer whereas others without rims may have formed in a crust with a methane-saturated layer. Post-processing (e.g., aeolian fill and fluvial erosion) also influences the crater rim and depth [1,2]. We will consider these effects in future works as we compare our results with the range of observed Titan craters.

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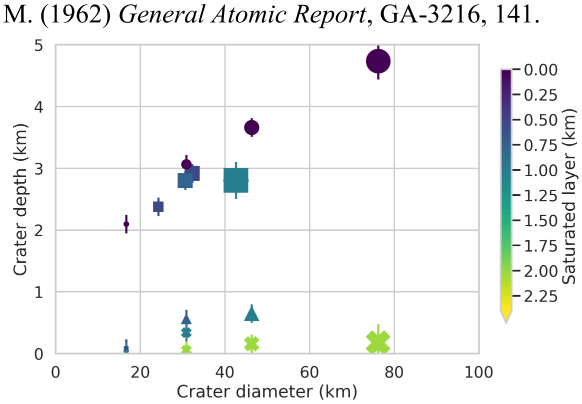

Figure 1: Crater depth as a function of crater diameter. Each symbol represents a different morphology of the crater (see text). The size of symbols corresponds to the diameter of impactors while the color indicates the thickness of the methane-saturated layer.

TITAN FROM MANY ANGLES: EVIDENCE FOR CHANGES IN METHANE AND AEROSOL VERTICAL PROFILES.

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Introduction: Titan's vertical distribution of aerosols was measured on 14-JAN-2005 by DISR, the Descent Imager/Spectral Radiometer instrument on the Huygens probe [1]. HASI (the Huygens Atmospheric Structure Instrument) measured atmospheric pressure and temperature from an altitude of about 1400 km down to the surface [2]. GCMS (the Gas Chromatograph Mass Spectrometer) measured vertical abundances of trace gases, including methane, the most optically active absorber in the 1 – 5 μm range [3]. Aerosol optical properties (optical depth, single scattering albedos and phase functions) derived from DISR have been used to help retrieve surface albedos through Titan's methane windows.

During the entire Cassini mission, from 2004 through 2017, the VIMS instrument (Visible and Infrared Mapping Spectrometer) obtained spectral image cubes of Titan during flybys. We report on radiative transfer (R-T) modeling of VIMS spectra and how the vertical profiles of methane and aerosols have changed since the Huygens probe obtained *in situ* data in 2005.

Method: Images of Titan's disk are limb-brightened in methane wavelengths, an effect attributed to the concentration of Titan's methane at low altitudes compared to the prevalence of aerosols at higher alttitudes. R-T modeling of Titan's disk does produce limb brightening when using the vertical profiles of methane and aerosols derived from Huygens instruments. A similar effect is observed as a function of emission angle: the same terrain observed from two emission angles will be brighter at the higher emission angle (lower elevation angle). However, the amount of limb brightening has changed over the course of the Cassini mission from what was observed in 2005. We use VIMS observations taken at a variety of observing geometries to retrieve methane and aerosol profiles as a function of latitude and time.

Results: The profiles from the Huygens probe instruments do not fit VIMS spectra obtained at later dates. For example, VIMS spectra obtained in flyby T66 (from January 2010, five years after the Huygens probe entry) show significantly *less* limb brightening than predicted if DISR, HASI and GCMS data were used. We present quantitative best-fit profiles for methane and aerosols as a function of time.

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Laboratory Experiments on Understanding Atmospheric, Surface, and Interior Processes on Titan. Xinting Yu[1,2], Yue Yu*[1], Taylor Duncan*[1], Kyle Kim*[1], Jialin Li*[2], Julia Garver*[2], Maggie Thompson[2], Ella Sciamma-O'Brien[3], Chao He[4], Joshua A. Sebree[5], Farid Salama[3], Sarah M. Hörst[4], Myriam Telus[1], Toyanath Joshi[2], David Lederman[2], Xi Zhang[1]. [1]Department of Earth and Planetary Sciences, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064 (xintingyu@ucsc.edu). [2]Department of Physics, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064. [3]NASA Ames Research Center, Space Science Astrobiology Division, Astrophysics Branch, Moffett Field, CA 94035. [3]Department of Earth and Planetary Sciences, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218. [5]Department of Chemistry and Biochemistry, University of Northern Iowa, 1227 W 27th St, Cedar Falls, IA 50614. *: undergraduate students at UC Santa Cruz.

Titan's nitrogen-methane atmosphere has enabled rich photochemistry to occur in its upper atmosphere. Energetic particles from Saturn's magnetosphere and UV photons from the Sun dissociate methane and nitrogen in Titan's upper atmosphere and induce complex chemical reactions, leading to the formation of complex organic particles (see, e.g., [1]). These refractory organic particles form the thick haze layers in Titan's atmosphere. During descent, the haze particles could interact with condensable species in Titan's stratosphere to ***form clouds***. Some of the hazes and the formed clouds would also fall through the atmosphere, eventually reaching the surface, where they could either ***interact with the surface liquids*** ([2]) or becoming surface sediments that partake in ***sediment transport and dune formation*** ([3]). My previous works have demonstrated that the material properties of the hazes can directly affect our understanding of these atmospheric and surface processes on Titan [4-7]. However, the conclusions are drawn from using a particular laboratory-made aerosol analog (the so-called "tholin") produced in one laboratory using one specific set of experimental conditions. We are conducting a cross-laboratory comparison study to assess various material properties of tholins using tholins samples produced in three independent laboratory facilities under a range of experimental conditions. We are also using Cassini-Huygens data to constrain these material properties, so we can ***confidently extrapolate the implications resulting from these tholin investigations to the aerosols on Titan.***

Note that the whole process of forming organics and depositing them on the surface is irreversibly destructing methane and would eventually lead to methane depletion in tens of Myrs [8]. Thus, a methane source is needed to explain the current methane abundances in Titan's atmosphere. A few theoretical studies have pointed out the possibility of primoradial organics in Titan's interior [9, 10]. The thermal instability of the organics could lead to methane release and thus ***replenish Titan's atmospheric methane***.

My group uses a combination of laboratory experiments and theoretical models to understand how the hazes partake in various atmospheric and surface processes, including cloud formation through haze-condensate interactions, haze-lake interactions, and surface sediment transport. We are also experimentally investigating the thermal instability of primordial organics and assessing how much atmospheric methane could be resupplied through this mechanism.

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