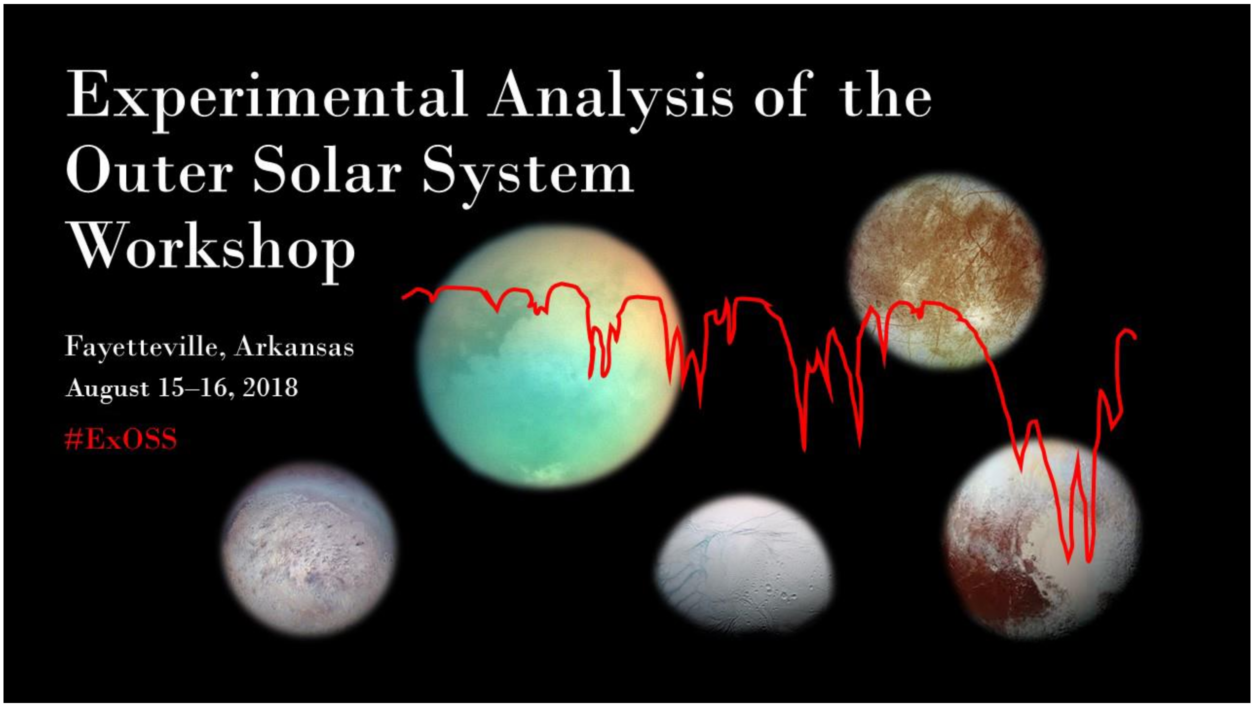

Program and Abstracts

Experimental Analysis of the Outer Solar System Workshop

August 15–16, 2018 • Fayetteville, Arkansas

Organizers

Lunar and Planetary Institute

Universities Space Research Association

Arkansas Center for Space and Planetary Sciences

Convener

Caitlin Ahrens
Arkansas Center for Space and Planetary Sciences

Science Organizing Committee

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Arkansas Center for Space and Planetary Sciences

Larry Roe
Arkansas Center for Space and Planetary Sciences

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Arkansas Center for Space and Planetary Sciences

Abstracts for this workshop are available via the workshop website at

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Lunar and Planetary Institute 3600 Bay Area Boulevard Houston TX 77058-1113

Guide to Sessions

Wednesday, August 15, 2018

9:00 a.m.	Room RCED 111	Registration
10:00 a.m.	Room RCED 111	Icy Bodies Part I: Compounds and Mixtures
2:00 p.m.	Room RCED 111	Pluto and Kuiper Belt Object Surfaces
2:30 p.m.	Room RCED 111	Delving into the Deep
3:30 p.m.	Poster Session Room	Poster Session: Experimental Analysis of Icy Bodies

Thursday, August 16, 2018

10:00 a.m.	Room RCED 111	Arkansas Center for Space and Planetary Sciences Laboratory Tour
1:00 p.m.	Room RCED 111	Icy Bodies Part II: Drilling into the Ice
2:30 p.m.	Room RCED 111	Exploration Through Laboratories — Facility Overviews

Program

Wednesday, August 15, 2018
ICY BODIES PART I: COMPOUNDS AND MIXTURES
10:00 a.m. Room RCED 111

Overview of experimental analyses regarding Titan and other icy bodies in the saturnian system.

10:00 a.m. Ahrens C. J. *
Welcome to the Experimental Analysis of the Outer Solar System Workshop

10:30 a.m. Chevrier V. F. * Farnsworth K.
Experimental Study of Nitrogen Dissolution in Methane-Ethane Mixtures Under Titan Surface Conditions **[#3014]**
We present new results on the thermodynamic and kinetic properties of nitrogen dissolution in liquid methane and ethane on Titan. N_2 is more soluble in methane than ethane, although kinetics are controlled by diffusion in the liquid phase.

11:00 a.m. Farnsworth K. K. * Chevrier V. F. McMahon Z. Laxton D. Soderblom J. M.
Experimental Detection of Nitrogen Bubbles in Methane-Ethane Liquid Under Titan Surface Conditions **[#3015]**
An experimental study of nitrogen exsolution in methane-ethane mixtures.

11:30 a.m. Czaplinski E. * Farnsworth K. Chevrier V.
An Experimental Study of Evaporites on Titan **[#3009]**
Titan's lakes of methane and ethane suggest that additional organics are also present in these liquid reservoirs. We simulate Titan's lakes in a chamber by combining various organic mixtures and studying their infrared spectra during evaporation.

12:00 p.m. LUNCH

1:30 p.m. Munsat T. * Ulibarri Z. Abel B. Dee R. James D. Kempf S. Kupihar Z. Sternovsky Z.
Generation and Detectability of Organic Compounds and CO_2 from Hypervelocity Dust Impacts Into Icy Surfaces in the Lab **[#3012]**
New experiments at the University of Colorado dust accelerator produce mass spectra from hypervelocity impacts into cryogenic targets. Early results indicate the survival and detection of complex organic molecules and CO_2.

Wednesday, August 15, 2018
PLUTO AND KUIPER BELT OBJECT SURFACES
2:00 p.m. Room RCED 111

Experimental analysis from the Pluto Simulation Chamber at the Arkansas Center for Space and Planetary Sciences.

2:00 p.m. Ahrens C. J. * Chevrier V. F.
Spectral Characteristics of Carbon Monoxide, Nitrogen, Methane Mixtures in Simulated Pluto Conditions **[#3006]**
Main ice components on Pluto can be mixed in a temperature-low pressure simulated environment for the purpose of interpreting spectral observations from New Horizons and future missions.

DELVING INTO THE DEEP
2:30 p.m. Room RCED 111

Laboratory research for icy body interiors.

2:30 p.m. Vance S. D. * Brown J. M. Bollengier O. Journaux B. Abramson E. H. Shaw G. Malaska M.
Delving into Ocean World Interiors **[#3013]**
We are advancing the state of the art for thermodynamic equations of state of ices and aqueous solutions for pressures up to and exceeding 1 GPa, and over a broad range of temperatures. These are needed for improving inversions of geophysical data.

3:00 p.m. DISCUSSION

POSTER SESSION: EXPERIMENTAL ANALYSIS OF ICY BODIES
3:30 p.m. Poster Session Room

Whittington A. G. Morrison A. A. Zhong F. Mitchell K. L. Carey E. M.
Rheological Investigation of Cryovolcanic Slurries **[#3003]**
We are studying the rheology of cryomagmas (ice-brine slurries) in the water-methanol-ammonia ternary system and in water-salt binary systems, using rotational viscometry from 0° to –0°C at MU, and to lower than –100°C at JPL.

Sternovsky Z. DeLuca M. Kupihar Z. Abel B. Kempf S. Munsat T. Postberg F. Ulibarri Z.
Exploring the Habitability of Icy Worlds Through Impact Ionization Mass Spectroscopy of Icy Dust Particles **[#3004]**
Icy dust particles can be mass-analyzed in situ at icy worlds through impact ionization. This method is very sensitive to organic and inorganic species embedded in the ice and thus has a high potential for assessing habitability.

Thursday, August 16, 2018
ARKANSAS CENTER FOR SPACE AND PLANETARY SCIENCES
LABORATORY TOUR
10:00 a.m. Meet in Room RCED 111

10:00 a.m. Chevrier V. *
Laboratory Tour
Tour of the Arkansas Center for Space and Planetary Simulations Laboratory to look at the variability of instrumentation.

11:30 a.m. LUNCH

ICY BODIES PART II: DRILLING INTO THE ICE
1:00 p.m. Room RCED 111

Research involving the structure of icy compounds on Titan.

1:00 p.m. Lorenz R. D. * Clark R. N. Curchin J. Hoefen T. Neish C. D.
Impact Toughness and Mohs Hardness of Simple Hydrocarbon and Nitrile Ices at Titan Temperatures **[#3010]**
Titan organics / Hydrocarbons are quite soft / But nitriles are tough.

1:30 p.m. Sparta J. Lorenz R. D. * Costa T. Rehnmark F. Zacny K.
Drilling into Titan Cryogenic Materials: Water-Ammonia Ice and Paraffin Wax **[#3008]**
Special Titan drill / Turns wax, ice, ammonia / To bite-sized pieces.

2:00 p.m. BREAK

EXPLORATION THROUGH LABORATORIES — FACILITY OVERVIEWS
2:30 p.m. Room RCED 111

Overview of facilities and capabilities for outer solar system exploration.

2:30 p.m. Hanley J. * Grundy W. Tegler S. Lindberg G.
Cryogenic Outer Solar System Materials at Northern Arizona University's Astrophysical Ices Laboratory **[#3016]**
NAU's Astrophysical Ices Lab offers a unique setup with a thick enclosed cell that allows visual, Raman, and transmission spectroscopy of materials down to 30 K.

3:00 p.m. Schauer Z. S. * Witiw R. W. Mardon A. M.
Benefits of Virtual Reality for Mental Health in Long-Term Space Exploration **[#3007]**
Virtual Reality is proposed as a practical solution to a vast number of fundamental mental health issues encountered in long-term space exploration rooted in isolated, confined, and extreme environments.

3:30 p.m. DISCUSSION AND CLOSING REMARKS

Notes

CONTENTS

SPECTRAL CHARACTERISTICS OF CARBON MONOXIDE, NITROGEN, METHANE MIXTURES IN SIMULATED PLUTO CONDITIONS. C. J. Ahrens[1] and V. F. Chevrier[1], [1]Arkansas Center for Space and Planetary Science, University of Arkansas, Fayetteville, AR 72701, (ca006@email.uark.edu).

Introduction: Ground-based telescopes and the NASA New Horizons fly-by advanced our understanding of the composition and geochemistry off the surface of Pluto. However, the development of physical and chemical models requires new laboratory data for interpreting mission observations.

The New Horizons Linear Etalon Imaging Spectral Array (LEISA) data consists of the observational wavelength range 1.25 µm – 2.5 µm [1]. Therefore, spectral data acquired under Plutonian conditions would be ideal to compare with LEISA data and for extending theoretical modeling of seasonal effects on ices and gases, Pluto's surface temperatures range from 33 K – 55 K with a surface pressure of approximately 10 – 25 µbar [2-3]. Preliminary compositional mapping shows Pluto to have differing spectral regions comprised of three main compounds: nitrogen (N_2), methane (CH_4), and carbon monoxide (CO) [4-5]. Differing ice abundances and interactions thereof play many roles in the development of mineralogical structure, different localized sublimation, and geological processes [5-7]. However, spectral characteristics of ice (binary and ternary) mixtures in the system N_2-CH_4-CO remain poorly studied.

CH_4 in N_2 is particularly of interest due to the observed presence of two phases: one highly diluted in solid beta-nitrogen and another that is still unknown, but hypothesized to be a segregated layer in patches or intimate with the diluted phase [8-9].

CH_4-CO mixture, however, has a lack of literature and experimental data at Pluto's low temperature and pressure conditions.

Finally, CO-N_2 mixtures also pose an interesting question to phase changes and behavior at low temperatures and pressures, as previous studies were mainly theoretical at low Plutonian conditions [10].

Experimental Approach: The Pluto simulation chamber at the W.M. Keck Laboratory for Space and Planetary Simulations at the University of Arkansas is 1.31 m. in length and 0.56 m. in diameter [11]. This stainless-steel vacuum chamber includes FTIR capabilities and a camera system for visual observation of the ice samples and phase behavior.

The experimental protocol for this task is as follows: a main gas constituent (for example, CO) is mixed in a set molar ratio with a second constituent (CH_4 or N_2) within a pre-mixing chamber connected to the simulation chamber. Then the mixture is injected into the cryo-vacuum pre-chilled simulation chamber at a temperature of 10 K and 14 µbar, and condenses onto the vertical coldhead where recording from the FTIR and camera begins. The mixture is then heated by 1 K, 5 K, or 10 K increments, which helps determine the temperature of phase transition detected by spectroscopy or optical instruments.

FTIR spectra is acquired using a Thermo Nicolet 6700 Spectrometer with a TEC InGaAs detector at a resolution of 2 and 450 second intervals. Long acquisition times allows a higher resolution to identify and separate more complex intimate mixtures.

The spectra are collected using the OMNIC software. Peak changes, shifts, band areas, and change of scattering effects (for potential amorphous phases) can be analyzed using this software for ice structure behavior.

Results: CH_4-N_2 mixtures, according to Prokhvatilov and Yantsevich [12], show specific phase transitions. N_2 alpha-beta transition occurs at ~35 K, whereas CH_4 II to CH_4 I transition occurs at ~21 K. Our spectral measurements at 1 K increments were able to detect noticeable peak changes in relation to these phase transition temperatures. The 2.2, 2.25, 2.33, and 2.38 µm methane bands are prominently shifted within the 19 K – 22 K transitionary range (Figure 1). Past the 21 K transition mark, the 2.2 µm band has disappeared.

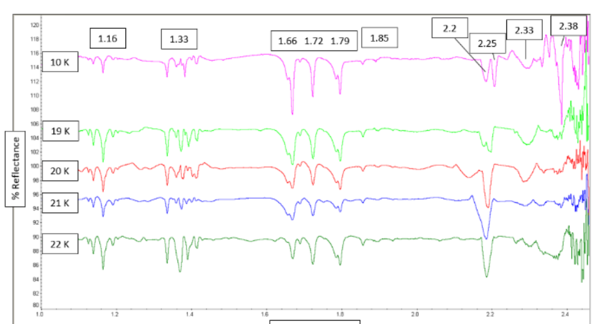

Figure 1: Spectra of 100 mol% CH4 at varying temperatures (10 K at top, then 19 K – 22 K in 1 K increments).

With the preliminary CO-N_2 mixtures, higher concentrations of CO masked the N_2 spectral signatures (Figure 2). However, at lower concentrations of CO were found to have a spectral behavior change below 30 K at 2.33 microns, next to the prominent 2.35 micron CO band. The ice characteristic at concentrations below 30% CO, and at temperatures below 35 K showed a possible glass-like microcrystalline structure in our optical observations [13]. This phase was verified with FTIR to show strong signals of CO at 2.35 µm, but minimize or disappear once temperatures reached 35 K (Figure 3).

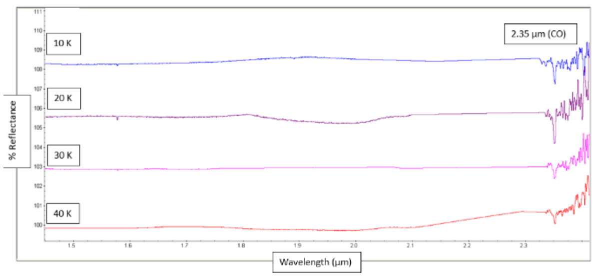

Figure 2: Spectra of 10 mol% N_2 with 90 mol% CO at varying temperatures (10 K at top, in 10 K increments).

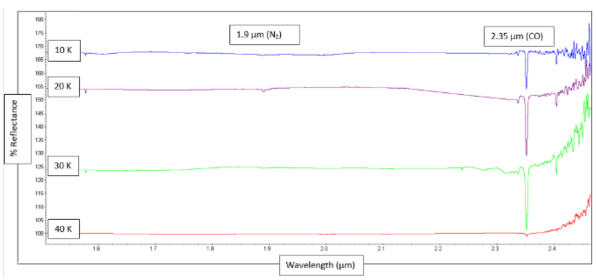

Figure 3: Spectra of 85 mol% N_2 with 15 mol% CO at varying temperatures (10 K at top, in 10 K increments).

With the preliminary CO-CH_4 mixtures, higher concentrations of CO masked certain CH_4 spectral modes, such as the branches usually seen in the 1.16 and 1.33 micron bands (Figure 4). However, the 2.2 micron methane band appears to "dull" or become masked as CH_4 increases (Figure 5), giving rise to the question of the 2.2 micron band behavior directly interacting with the increased ratio of CO present.

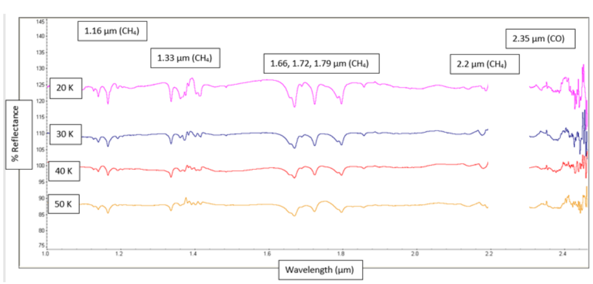

Figure 4: Spectra of 20 mol% CH_4 with 80 mol% CO at varying temperatures (20 K at top, in 10 K increments).

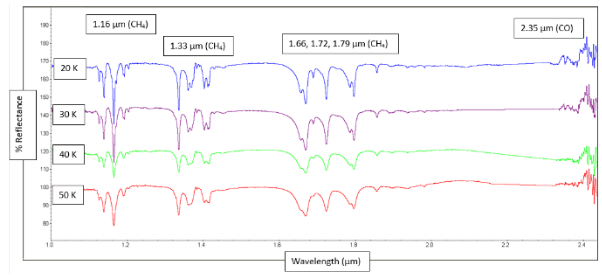

Figure 5: Spectra of 50 mol% CH_4 with 50 mol% CO at varying temperatures (20 K at top, in 10 K increments).

Conclusions: CH_4-N_2 mixtures show the phase transitions using the FTIR instrumentation, allowing for further investigation to other potential phase transitions with other mixtures.

CO-N_2 mixtures potentially show a spectral transition < 35 K at lower ratios of CO as detected visually and spectrally. This observed behavior could influence the evolution of certain mineralogical aspects of Pluto, such as boundary layers and glaciation [3-4].

CO-CH_4 mixtures show a possible interaction of certain methane spectral bands having possible dependence on the molar ratio amount of CO present.

Laboratory measurements of planetary surface compositions provide crucial support to science instrument measurements from ground-based, orbital, and lander observations. Currently, there is a deficient number of facilities to measure the properties of low temperature/pressure ices relevant to Pluto and other Kuiper Belt Objects. Extremely low conditions (< 90 K, microbar pressures) and exotic ice materials have been little studied due to challenging experimental constraints.

References:

[1] Reuter D. C. et al. (2008) Space Science Reviews, 140, 129. [2] Lorenzi, V. et al. (2015), AAS DPS 47, Abstract 210.08 [3] Cruikshank, D., et al. (2015), Icarus, 246, 82-92. [4] Stern, S. et al. (2015), AAS DPS 47, Abstract 100.01 [5] Kim, Y., Kaiser, R. (2012) The Astrophysical Journal, 758:37, 1-6. [6] Schmitt, B. et al. (2017) Icarus, 287, 229-260. [7] Moore, J. et al. (2016) Science, 351:6279, 1284-1293. [8] Schmitt, B. et al. (2016), LPSC XLVII, Abstract 2794. [9] Doute, S. et al. (1999) Icarus, 142:2, 421-444. [10] Angwin, M., Wasserman, J. (1966) Journal of Chem. Phys., 44:1, 417-418 [11] McMahon, Z. et al. (2016) LPSC XLVII, Abstract 1728. [12] Prokhvatilov, A., Yantsevich, L., (1983) Sov. J. Low Temp. Phys. 9(2), 94-98. [13] Ahrens, C. et al. (2017) LPSC XLVIII, Abstract 1352.

EXPERIMENTAL STUDY OF NITROGEN DISSOLUTION IN METHANE-ETHANE MIXTURES UNDER TITAN SURFACE CONDITIONS. V.F. Chevrier[1], K. Farnsworth[1], [1]University of Arkansas, Arkansas Center for Space and Planetary Sciences STON F47, University of Arkansas, Fayetteville, AR 72701 (vchevrie@uark.edu).

Introduction: Besides Earth, Titan is the only known planetary body with a thick nitrogen (N_2) atmosphere, and stable liquids on its surface. Titan's N_2 atmosphere and smaller atmospheric constituent, methane (CH_4), allows the moon to have a methane hydrologic cycle [1] and the minor presence of ethane (C_2H_6), through methane photolysis [2]. These processes create stable CH_4-C_2H_6 dominated lakes on Titan's surface [3]. However, the exact composition of these lakes is still under debate, particularly regarding the contribution of dissolved nitrogen [4,5]. This is due to the lack of experimental data regarding surface temperature and pressure conditions, causing the thermodynamic and kinetic parameters to remain uncertain. The solubility of dissolved nitrogen [6] is particularly important to interpret recent radar observations of transient features called 'Magic Islands' [7]. These observations were further modeled to show nitrogen bubble formation as a likely candidate [8,9]. Therefore, this study aims to determine the thermodynamic and kinetic solubility of nitrogen in liquid methane / ethane under Titan surface conditions.

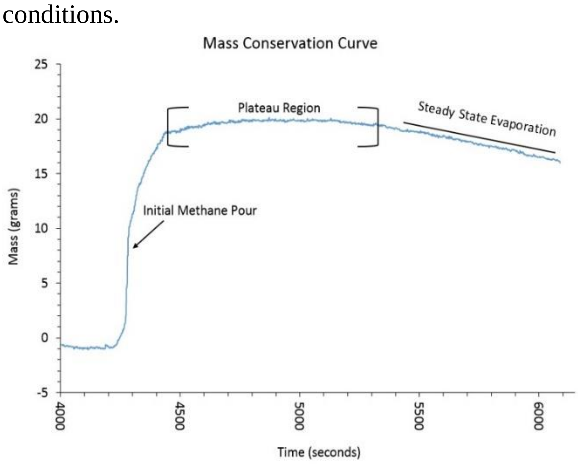

Figure 1. Mass as a function of time for pure methane. This plot shows the two different regimes observed in the experiments: a plateau zone immediately after the methane pour (here from ~4400 to 5300 s), followed by steady-state evaporation.

Methods: The experiments were conducted at the University of Arkansas in a Titan surface simulation chamber [10]. This chamber retains temperatures of 85 – 100 K and pressure of 1.5 bar using liquid N_2 and gas, respectively. The methane and/or ethane sample is condensed into the liquid phase and is expelled onto a petri dish connected to a hanging electronic balance. Sample mass, temperature (atmosphere and sample) and pressure are recorded for the duration of the experiment.

Data Analysis: Mass curves for methane and methane / ethane mixtures exhibit two different regimes (Fig. 1): (1) a mass increase corresponding to nitrogen dissolution (the so-called plateau section); (2) steady-state mass loss corresponding to the evaporation of the liquid phase [11,12]. The "plateau" results from the mass balance between methane evaporation and nitrogen dissolution. Evaporation rates of methane and methane-ethane mixtures are then determined from a least-square fit to the steady-state portion of the mass vs. time curves [3, 5] and the deviation from this initial evaporation rate (the plateau region) gives the apparent mass of dissolved nitrogen. Therefore, correcting the curves for the steady-state evaporation provides the nitrogen solubility as a function of time. The maximum of the curve (at "infinite" time) provides the saturation value.

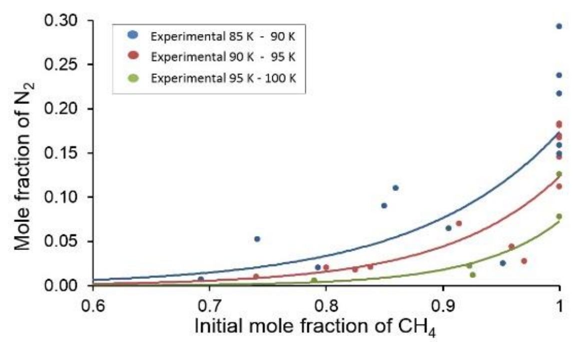

Figure 2. Mole fraction of dissolved N_2 as a function of initial mole fraction of CH_4 in a CH_4-C_2H_6 mixture. An exponential increase of N_2 solubility is observed with increasing CH_4 concentration above 0.7 mole fraction of CH_4, and a decreasing mole fraction with increasing temperature.

Results: The data regarding the dissolution of nitrogen in pure methane and methane-ethane mixtures is shown in Figure 2 and Figure 3. As the concentration of methane increases, the percentage of dissolved nitrogen exponentially increases (Fig. 2). Regarding pure methane, as the temperature of the liquid decreases, the solubility of nitrogen increases (Fig. 3). Even though there is some discrepancy regarding the slope of the exponential trend, the relationship between percent methane, temperature, and percentage of dissolved nitrogen is clearly present.

The dissolution of nitrogen in methane-ethane mixtures sharply increases from ~1 mol% N_2 at 74 mol% CH_4, to ~20 mol% N_2 in 100% CH_4. There is no observable N_2 dissolution in pure liquid ethane, confirming previous observations [6,11]. Hence, we assume it is negligible in ethane-rich samples at the time scale of our experiments (~ 4 hours).

The relatively large spread of N_2 solubility data results from temperature variation in the liquid (Fig. 2). This is particularly apparent when the data are binned in 5 K increments. Higher temperatures result in lower N_2 solubility, which decreases by a factor ~2 between 85 and 95 K.

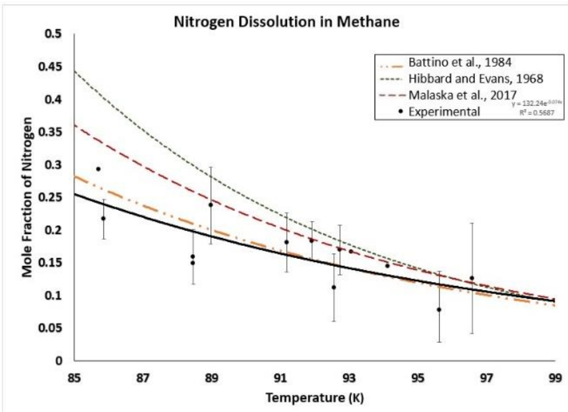

Figure 3. N_2 dissolution in 100% CH_4 as a function of temperature, compared to other experimental models [6,13,14].

Dissolution Kinetics: We assume in this section that the dissolution of nitrogen in methane is controlled by the diffusion of nitrogen molecule in liquid methane at the interface liquid-atmosphere. To describe this process we use a classic Fick's derived solution for diffusion in a semi-finite depth, modified to account for the evaporation of the liquid (and therefore a change of depth) using the following equation (1):

$$m(t) = \left[A \times C_0 \times \left[erfc\left(\frac{L}{2\sqrt{Dt}}\right) + \left(\frac{2\sqrt{Dt}}{\sqrt{\pi}}\right) \times \left(1 - \frac{L^2}{e^{4Dt}}\right)\right]\right] - Et$$

Where A is the surface area of the sample, C_0, the concentration at the interface (saturation), L is the thickness of the sample at t_0, D the diffusion coefficient, E the evaporation rate, and t time. In this case, we do not correct for the steady-state portion of the data, but fit all the data after just scaling for the initial methane or mixture pour (Fig. 4).

Results show that equation (1) provides a remarkably good fit of the data, using C_0, D and E as free parameters. So far we have determined diffusion coefficients D ranging from 2.62 to 8.00×10^{-10}, with an average of 5×10^{-10} m^2s^{-1}. The concentration at saturation (C_0) is in the same range as the concentrations determined by the "plateau" method.

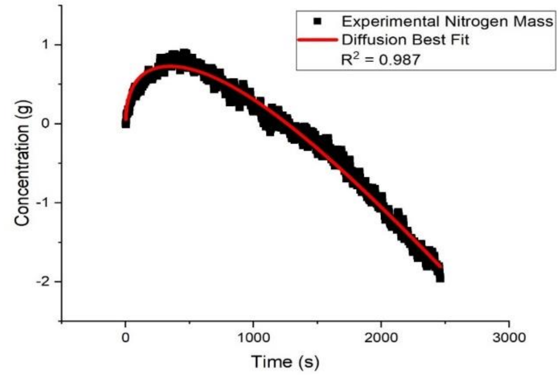

Figure 4. Nitrogen mass vs. time in pure methane. The red line is the fit using diffusion in a semi-finite medium modified for methane evaporation described by equation (1).

Conclusions: This study demonstrates that nitrogen is more soluble in methane than ethane and dependent on the temperature of the liquid. Therefore, a small change in Titan's surface temperature can strongly influence the concentration of dissolved nitrogen in Titan's lakes. Moreover, kinetic calculation show that N_2 dissolution occurs very slowly. Therefore, unless liquid-rich methane rains saturate directly in the atmosphere, lakes would be strongly out of equilibrium with the atmosphere. At the scale of half a season (15 years), only the first 20 cm of a lake would be 90% saturated. This could potentially result in strong disequilibria between deep and superficial layers in the lakes and therefore strong dynamics.

Acknowledgements: This work was funded by NASA Outer Planets Research grant #NNX10AE10G and the NASA Cassini Data Analysis Grant #NNX15AL48G.

References: [1] Lunine J. I., S. K. Atreya (2008) *Nat. Geosci.* 1 (3), 159. [2] Wilson E. H., S. Atreya (2004) *J. Geophys. Res.: Planets* 109 (E6). [3] Brown R. H. et al. (2008) *Nature* 454 (7204), 607-610. [4] Cordier D. et al. (2009) *Astrophys. J. Let.* 707 (2), L128. [5] Glein C. R., E. L. Shock (2013) *Geochem. Cosmochem. Acta* 115, 217-240. [6] Malaska M. J. et al. (2017) *Icarus* 289, 94-105. [7] Hofgartner J. et al. (2014) *Nat. Geosci.* 7 (7), 493. [8] Cordier D. et al. (2017) *Nature Astro.* 1 (5), 0102. [9] Farnsworth K. et al., in *Lunar and Planetary Science Conference*. (The Woodlands, TX, 2018), vol. XLIX. [10] Wasiak F. C. et al. (2012) *Adv. Space Res.* 51 (7), 1213-1220. [11] Luspay-Kuti A. et al. (2015) *Earth Planet. Sci. Lett.* 410, 75-83. [12] Luspay-Kuti A. et al. (2012) *Geophys. Res. Lett.* 39 (L23203). [13] Hibbard R. R., A. Evans, *On the solubilities and rates of solution of gases in liquid methane* (National Aeronautics and Space Administration, 1968). [14] Battino R. et al. (1984) *J. phys. and chem. ref. data* 13 (2), 563-600.

AN EXPERIMENTAL STUDY OF EVAPORITES ON TITAN

E. Czaplinski[1], K. Farnsworth[1], and V. Chevrier[1]. [1]University of Arkansas, Center for Space and Planetary Sciences, Fayetteville, AR 72701. (ecczapli@email.uark.edu)

Introduction: Titan's dynamic lakes of liquid methane/ethane have intrigued scientists for over a decade. Using the Visual Infrared Mapping Spectrometer (VIMS) onboard Cassini, regions described as 5-μm-bright were first observed in the Xanadu (110°W, 15°S) and Tsegihi (15°W, 40°S) Regios [1]. In-depth studies of these 5-μm-bright regions have concluded that they are non-water ice materials, similar to the 5-μm-bright signatures found in the Tui and Hotei Regios (near 25°S) [2]. A 5-μm-bright ring was also found around Ontario Lacus [3,4]. Described as "bathtub rings" of low water ice condensates, they may have been deposited in the past when lake levels were higher. Further, VIMS observations identified additional 5-μm-bright annuli surrounding many empty north polar lakes [5,6]. Combined, these observations provide the foundation on which evaporites can be studied on Titan.

Current evaporite studies focus on models and theoretical work [7,8], but some experimental work is also being undertaken to constrain potential solvents and solutes that may be active in evaporite production [9-12]. This study expands the compounds studied by analyzing ethylene (C_2H_4), benzene (C_6H_6), and acetylene (C_2H_2) evaporites.

Methods: The University of Arkansas owns a specialized Titan simulation chamber that reproduces the same conditions that are present on Titan's surface [13]. This chamber is unique in that it provides real-time experimental data on the composition of Titan's lakes. The chamber is made of stainless steel with a height of 2.08 m and internal diameter of 0.61 m. A 1.5 bar atmosphere is maintained with N_2. Temperatures of 90 K – 94 K are reached with the use of a liquid nitrogen refrigeration system. Liquid nitrogen flows through copper cooling coils and cryogenic lines that surround the chamber and temperature control box (TCB). The TCB is cooled using this method, while the rest of the chamber serves to maintain the atmospheric pressure of 1.5 bar.

Compounds in gaseous phase at room temperature (CH_4, C_2H_6, C_2H_2, C_2H_4) are contained in gas cylinders, and introduced to the condenser via gas lines. C_6H_6, however, is a liquid at room temperature, so an Erlenmeyer flask was modified and connected to the condenser. N_2 is bubbled through the Erlenmeyer flask for ~10 min until the N_2 is saturated with respect to C_6H_6. Then, the line to the condenser is opened, which allows N_2 to carry gaseous C_6H_6 into the condenser where C_6H_6 condenses in the solid phase. After the compounds are added to the condenser and given time to condense and dissolve into the solvent, a solenoid valve is turned on, which allows the sample to be transferred from the condenser to the petri dish at the bottom of the chamber. The petri dish is covered with a layer of Spectralon® reflectance material, which serves as a background for two way transmission infrared spectral measurements. Here, the sample is analyzed via Fourier transform infrared (FTIR) spectroscopy probes connected to a Nicolet 6700 FTIR (wavelength 1–2.5 μm).

Results and Discussion:

Ethylene: Three different experiments were analyzed for C_2H_4 evaporites: CH_4/C_2H_4 (Fig. 1), C_2H_6/C_2H_4, and $CH_4/C_2H_6/C_2H_4$. Through band depth measurements, mass data, and spectral data, we determined that an C_2H_4 evaporite deposit only formed in the CH_4/C_2H_4 experiment (Fig. 1). CH_4 evaporation observed at Titan supports the fact that CH_4 evaporates at Titan conditions in our chamber. We also observed horizontal band shifts in the characteristic C_2H_4 absorptions (1.64 and 2.12 μm) (Fig. 1B, 1C). This band shift represents a phase change of the mixture from liquid phase to solid phase. Additionally, we observed the persistence of a band at 1.66 μm (Fig. 1D). This band was unusual in the fact that it was present in pure CH_4, however band depth measurements confirmed complete CH_4 evaporation by the end of the experiment.

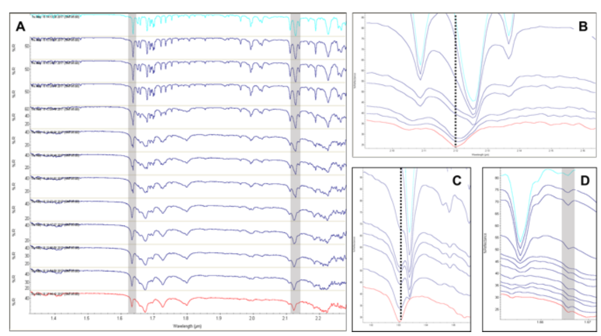

Fig. 1. Spectra from the CH_4/C_2H_4 experiment. **(A)** Offset spectra, initial spectrum in red (bottom), final spectrum in cyan (top). Gray rectangles highlight C_2H_4 absorbances at 1.63 μm and 2.12 μm. **(B, C)** Zoom of the 1.63 μm and 2.12 μm bands to show horizontal redshift. **(D)** Persistence of the 1.66 μm feature (shaded).

Benzene: We performed benzene experiments in both CH_4/C_6H_6 and C_2H_6/C_6H_6 mixtures. Similar to the CH_4/C_2H_4 experiment, we observed the persistence of a band at 1.66 μm, even after all other CH_4 bands were not present. When compared to the pure C_6H_6 spectrum from that experiment, the 1.66 μm band is the only difference (Fig. 2).

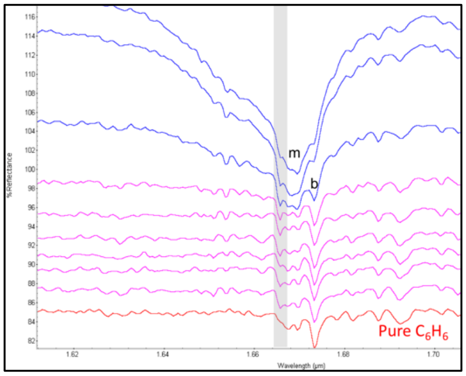

Fig. 2. Spectra from the CH_4/C_6H_6 experiment showing evaporation of the CH_4 triplet (m) from top to bottom. Benzene band denoted by “b”. Gray rectangle highlights the 1.66 μm band.

For the C_2H_6/C_6H_6 experiments, we initially maintained the sample at Titan temperatures (90 K), however no evaporite formed since C_2H_6 does not readily evaporate at Titan conditions [14]. After warming the mixture to ~120 K, sustaining for 20 minutes, then cooling back to 90 K, we observed the appearance and persistence of a band at 1.936 μm (Fig. 3). We hypothesize that this feature could represent the formation of a co-crystal, since this warming/cooling cycle resulted in co-crystal formation in other groups’ experiments [10-12].

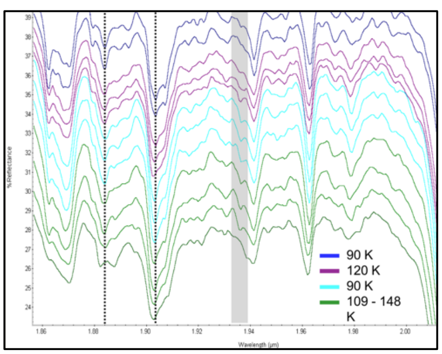

Fig. 3. Spectra of the C_2H_6/C_6H_6 experiment (initial at top, final at bottom). Dashed lines show horizontal band shifts, gray rectangle highlights the appearance of the 1.936 μm band.

Acetylene: Our last set of experiments focused on mixtures of acetylene (C_2H_2) and C_2H_6. Before performing this experiment, we first took spectra of pure C_2H_2 from 88 K–185 K and concluded that C_2H_2 undergoes three spectrally distinct ice phases (Fig. 4). We then tested a mixture of C_2H_6/C_2H_2 and confirmed the presence of these three ice phases (Fig. 4). We observed band shifts in all C_2H_2 bands present, an increase in band depth for the C_2H_2 1.55 μm band, and a decrease in band depth for the C_2H_2 1.93 μm feature (Fig. 4). These results were consistent with the pure C_2H_2 experiment. We did not observe the appearance or persistence of any additional bands that could indicate the formation of a co-crystal.

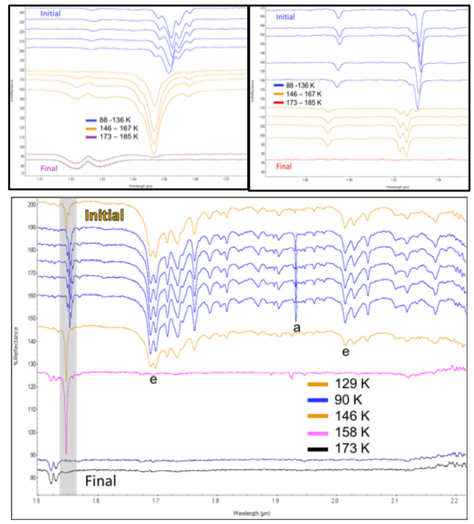

Fig. 4. Pure C_2H_2 spectra (top), and spectra from the C_2H_6/C_2H_2 experiment. Gray rectangle shows change in C_2H_2 bands throughout the temperature phases.

Conclusions: Under Titan conditions, we experimentally formed C_2H_4 evaporites in a solution of CH_4. The formation of the C_2H_4 evaporite is confirmed by observations of spectral data and band depth measurements. We also observed a horizontal band shift to longer wavelengths in the characteristic C_2H_4 bands. Additionally, we observed the appearance of new bands in a C_2H_6/C_6H_6 mixture, and distinct ice phases in a mixture of C_2H_6/C_2H_2. These results insinuate interesting chemistry is occurring in Titan’s lakes. Understanding more about the composition of Titan’s evaporites can help unlock these mysterious for future exploration.

Acknowledgements: This work was funded by NASA NESSF grant 17-PLANET17F-0092.

References: [1] Barnes, J.W. et al. (2005) *Science, 310,* 92-95. [2] MacKenzie, S.M. and Barnes, J.W. (2016) *ApJ, 821,* 1-13. [3] Barnes, J.W. et al. (2009a) *Icarus, 201,* 217-225. [4] Cornet, T. et al. (2012) *Icarus, 218,* 788-806. [5] Hayes, A. et al. (2008) *GRL, 35,* L09204. [6] Barnes, J.W. et al. (2011) *Icarus, 216,* 136-140. [7] Cordier, D. et al. (2013) *Icarus, 226, 1431-1437.* [8] Cordier, D. et al. (2016) *Icarus, 270,* 41-56. [9] Singh, S. et al. (2017) *GCA, 208,* 86-101. [10] Cable, M. L. et al. (2014) *GRL, 41,* 5396-5401. [11] Vu, T. H. et al. (2014) *J. Phys. Chem. 118,* 4087-4094. [12] Cable, M. L. et al. (2018) *ACS Earth Space Chem. 2,* 366-375. [13] Wasiak, F.C. et al. (2012) *Adv. Space Res.* [14] Luspay-Kuti, A. et al. (2015) *EPSL, 410,* 75-83.

EXPERIMENTAL DETECTION OF NITROGEN BUBBLES IN METHANE-ETHANE LIQUID UNDER TITAN SURFACE CONDITIONS. K. Farnsworth[1], V. Chevrier[1], Z. McMahon[1], D. Laxton[1], J. M. Soderblom[2]. [1]University of Arkansas, Center for Space and Planetary Sciences FELD 202, University of Arkansas, Fayetteville, AR 72701. (kkfarnsw@email.uark.edu). [2]Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, 77 Massachusetts Ave, Cambridge, MA 02139.

Introduction: Titan is the only body in the Solar System, besides Earth, with a dense nitrogen atmosphere and stable surface liquids. Titan's atmosphere is predominantly nitrogen, with several percent methane, which enables a methane hydrologic cycle [1]. Ethane also participates in this cycle and is generated via methane photolysis [2]. This atmosphere creates an environment in which lakes of methane and ethane are stable on Titan's surface [2]. Since nitrogen is attracted to methane, Titan's lakes and seas are predominately composed of methane-ethane-nitrogen. Nitrogen dissolution has been quantified in the laboratory [3,4] and prefers methane-rich liquids and colder temperatures [3,4,5].

Cassini RADAR has detected RADAR bright transient features in Titan's lakes, called "Magic Islands" [6,7]. These features are hypothesized to be suspended solids, floating ice, or more favored, waves, or *bubbles* [6,7]. To determine if bubbles are the cause of this phenomena, we must first understand how they form under Titan surface conditions.

This study focuses on quantifying the nitrogen exsolution process. We explore the relationship between liquid methane, liquid ethane, nitrogen gas, and temperature. Our work helps to better understand the thermodynamic processes that may occur in Titan's surface liquids and to determine if bubble formation is a likely candidate for the creation of Magic Islands.

Methods: Experiments were conducted in the University of Arkansas' Titan surface simulation chamber [8]. This chamber maintains a temperature of 85-100 K and a pressure of 1.5 bar using liquid and gaseous nitrogen, respectively. The sample gas (methane and ethane) is condensed into liquid phase in a condenser and is delivered into a petri dish connected to a hanging electronic balance. Due to its larger stability, ethane is added first to the petri-dish , followed by methane. Once the liquid has accumulated in the petri dish, the temperature is lowered to 85 K and the sample is allowed to equilibrate for at least 30 minutes. This allows optimal nitrogen dissolution into the mixture. Next, the liquid is warmed to 100 K to induce nitrogen exsolution. Mass and temperature are continuously recorded for the duration of the experiment.

Results/Discussion: Exsolution in the form of bubbles has been experimentally detected and have 3 main characteristics: (1) methane and ethane are required; (2) is dependent on methane-ethane ratio; and (3) bubbles have detectable energy loss. As the mixture is warming, bubbles are seen moving under a surface layer before further warming allows them to reach the surface (Fig. 1). These surface bubbles have a bi-modal size distribution with the smaller bubble diameter averaging 1.3 mm and the larger averaging 4.3 mm and a population density of 10.51 bubbles/cm^2.

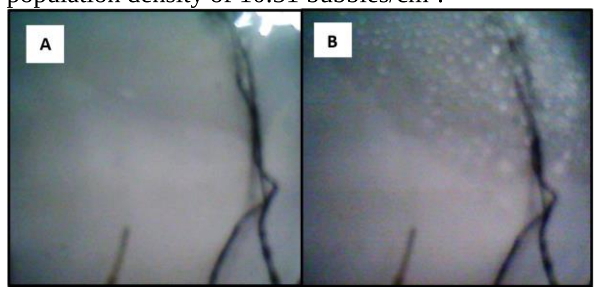

Figure 1: Before (A) and during (B) a bubble outgassing event.

We find that bubbles do not occur in pure methane or ethane, however, both are necessary for formation. The amount of degassing observed depends on the ratio with a gaussian fit and optimal bubble production at 68 mol% methane (Fig. 2). Bubble episodes have been observed to last between 2-12 minutes depending on this ratio. We propose that lowering the temperature to 85 K may freeze the ethane within the mixture. If the mixture is completely homogeneous, bubble formation does not occur.

Bubble outgassing episodes release energy which is measured as sharp temperature dips reaching approximately 10 K in 10 seconds (Fig. 3). This significant decrease in temperature indicates substantial amounts of energy being removed from the liquid by the degassing process, since nitrogen exsolution is endothermic.

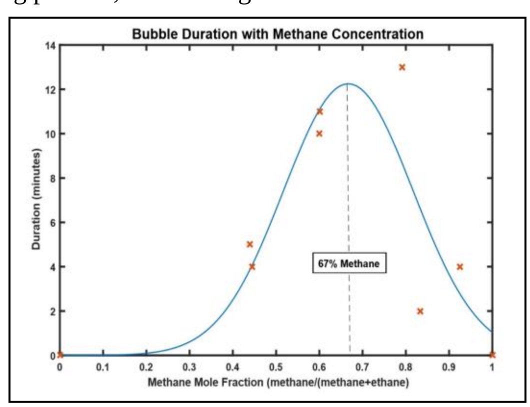

Figure 2: Bubble formation duration as a function of initial methane-ethane ratio.

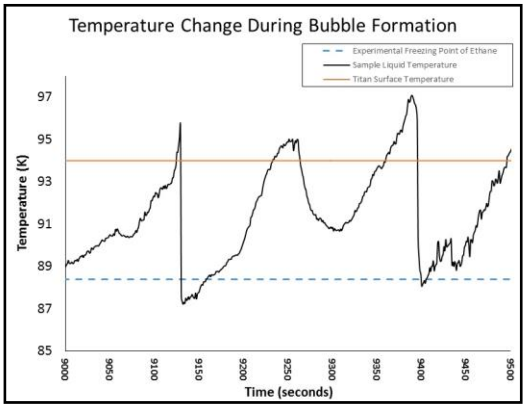

Figure 3: Temperature as a function of time during warming of a initially cold mixture of methane and ethane Note the strong temperature decrease during bubble release episodes.

We propose that bubble formation needs three important factors to occur: (1) nitrogen saturated methane; (2) sudden temperature increase; (3) a physical boundary between liquids. The temperature decrease and 30 minute timeframe at 85 K, described in the methods section, allows the saturation of nitrogen into methane [9]. During this process, methane becomes denser and sinks to the bottom of the liquid. The ethane-rich frozen top layer then insulates the nitrogen-methane-rich bottom layer during warming, preventing slow evaporation of nitrogen. Once the liquid warms passed ethane's melting point (90 K), ethane dissolves back into the mixture. At this moment the bottom methane-rich layer becomes strongly supersaturated with respect to nitrogen at these higher temperatures and ethane content, causing the system to reequilibrate. This ultimately results in a sudden nitrogen exsolution episode in the form of bubbles. This hypothesis is known as the liquid evolution model (Fig. 4).

Implications for Titan: In our experiments, bubbles are created near Titan temperatures and thus could be the source of the Magic Island. These experiments prove that bubble formation is possible and can last several minutes in only < 1 mm of liquid. On Titan, Ligeia Mare (for example) reaches 160 m in depth [10] allowing possible longer time scale outgassing. Bubbles may form by cold methane runoff entering a warm methane-ethane lake or warm ethane flowing into a cold methane dominated lake. They may also form when nitrogen saturated methane sinks to depth in a lake and intermixing with a bottom layers consisting of settled lake constituents. These processes may cause compositional lake circulations. Further modeling is necessary to understand how nitrogen dissolution and exsolution might affect lake circulation dynamics.

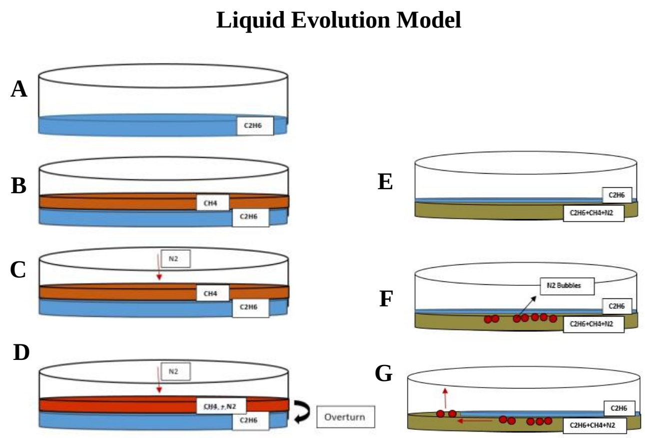

Figure 4: Liquid evolution model. A hypothesis of bubble formation.

Summary: This study presents experimental nitrogen bubble detection under Titan surface conditions. We find that bubble formation and duration depend on methane-ethane ratios and exhibit detectable energy loss. We propose that methane and ethane are necessary for bubble formation in our chamber and thus a physical barrier, nitrogen saturated methane, and a sudden temperature increase is needed for sudden outgassing. River runoff of varying concentrations and temperatures may be the source of Titan's Magic Islands. Nitrogen dissolution and exsolution may also drive chemical lake circulations. Our results show that Titan's lakes are more dynamic than previously expected.

Acknowledgements: This work was funded by NASA Outer Planets Research Grant #NNX10AE10G and Cassini Data Analysis Grant #NNX15AL48G.

References: [1] Lunine J.. and Atreya S. K. (2008) *Nature Geosci., 1*, 335. [2] Wilson E. H. and Atreya S. K. (2004) *JGR 109:*E06002 [3] Malaska et al. (2017) *Icarus, 289*, 94-105. [4] Farnsworth et al., (2018) *LPSC XLIX*, #2709. [5] Battino R. et al. (1984) *J. Phys. Chem. Ref. Data 13,* 563. [6] Hofgartner et al., (2014) *Nature Geosci., 7*, 493-496. [7] Hofgartner et al., (2016) *Icarus, 271*, 338-349. [8] Wasiak F. C. et al. (2013) *ASR 51*, 1213-1220. [9] Chevrier et al. (2018) *ExOSS Abstract.* [10] Mastrogiuseppe et al. (2014) *GRL, 41*, 5.

LABORATORY STUDIES OF CRYOGENIC OUTER SOLAR SYSTEM MATERIALS AT THE NORTHERN ARIZONA UNIVERSITY ASTROPHYSICAL ICES LABORATORY. J. Hanley[1], W. Grundy[1], S. Tegler[2], G. Lindberg[2]. [1]Lowell Observatory, Flagstaff, AZ (jhanley@lowell.edu), [2]Northern Arizona University, Flagstaff, AZ.

Introduction: The Physics and Astronomy Department at NAU hosts the Astrophysical Ice Laboratory, which is dedicated to studying ices under controlled temperatures and pressures [1-5]. Simple molecules like CH_4, H_2O, N_2, CO, CO_2, O_2, CH_3OH, C_2H_6, and NH_3 are important geological materials in the cold, outer regions of the solar system. Their mobility and distinct material properties enable geological activity and produce a spectacular variety of exotic landforms, even at extremely low temperatures. But frustratingly little is known of the basic mechanical and optical properties of these volatile ices, and especially of their mixtures.

Many outer Solar System bodies exhibit interesting phenomena that indicates active processes on geologically recent timescales. For instance, New Horizons imaged what appears to be flows of nitrogen ice on Pluto (Figure 1 top), possibly created through convective cells of buoyant nitrogen ice. How does nitrogen ice behave at these temperatures and pressures?

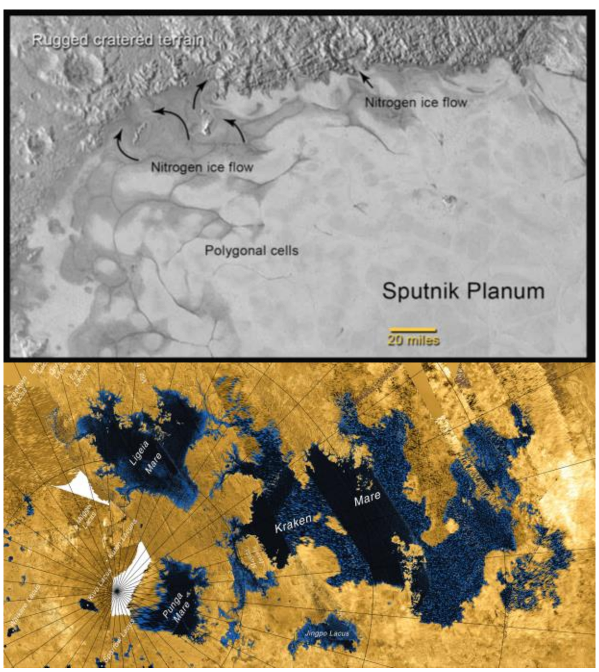

Figure 1. *Top: In the northern region of Pluto's Sputnik Planitia, swirl-shaped patterns of light and dark suggest that a surface layer of exotic ices has flowed around obstacles and into depressions, much like glaciers on Earth. Image and caption credit: NASA/JHUAPL/SwRI. Bottom: Hydrocarbon seas on Titan. Image credit: NASA/JPL-Caltech/Agenzia Spaziale Italiana/USGS.*

What happens when it is mixed with other species, such as carbon monoxide or methane? On Titan, we see lakes and seas of liquid hydrocarbons, as well as geologic features related to them such as river channels and shorelines (Figure 1 bottom).

The Astrophysical Ices Laboratory: Our cryogenic laboratory setup at Northern Arizona University (NAU) allows us to explore various properties of cryogenic materials at temperatures and pressures relevant to the outer Solar System.

Within the laboratory setup (Figure 2 top), volatile ices are condensed as thin ice films on a cold mirror, or within an enclosed cell (Figure 2 inset). Cooling is provided by closed-cycle helium refrigerators, within vacuum chambers for insulation. Samples can be cooled to 6 K on the thin film side, and ~30 K on the enclosed cell side. Cryogenic ice samples are studied via various analytical techniques including visible and infrared transmission spectroscopy, photography, and Raman spectroscopy (Fig 2 bottom). Mass spectrometers are capable of monitoring changes in composition.

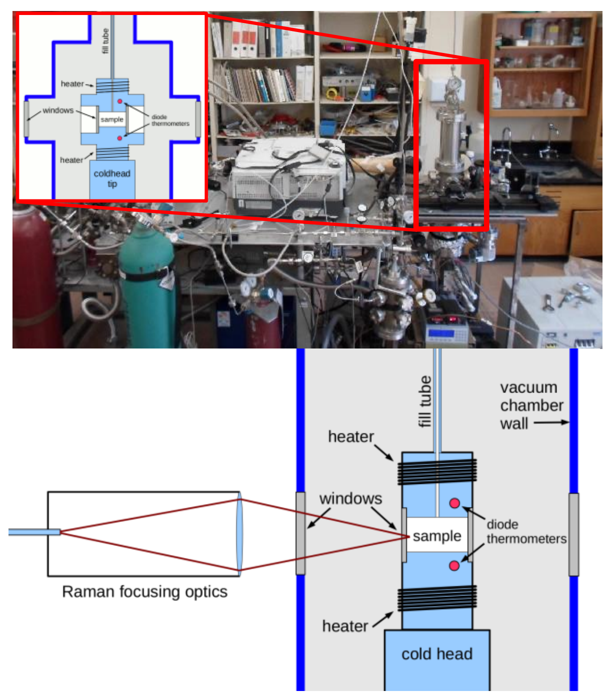

Figure 2. *Top: Photo of laboratory setup. Inset: Schematic of the cell. Bottom: Schematic of Raman optics.*

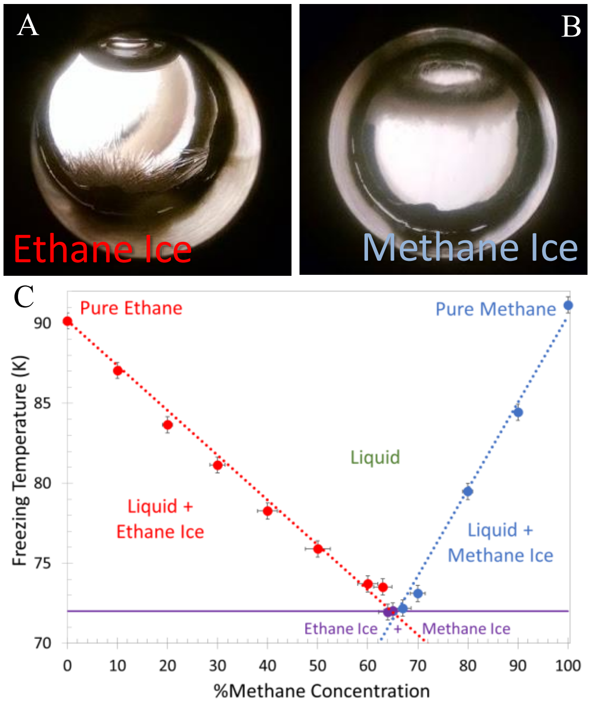

Figure 3. *Freezing points of solutions with varying methane/ethane concentrations. (A-B) Images of mixed methane and ethane solutions at their freezing points. Ethane ice freezes first (A) when the concentration falls on the ethane liquidus (red line in C), whereas methane ice forms on the top of the solution (B) when on the methane liquidus (blue line).*

Science Results: Some exciting results include applications to New Horizon's infrared observations of Pluto, understanding the seas of Titan, and studying the surface of Europa. The ices that can be created in the lab are useful to a variety of outer Solar System bodies.

For instance, any mixing of methane and ethane together will depress the freezing point of the lake below Titan's surface temperature, preventing them from fully freezing (Fig. 3C). Also, when ethane ice forms, it freezes on the bottom of the liquid (Fig 3A), while methane ice freezes at the top of the liquid (Fig 3B), implying ethane ice is denser than the solution, while methane ice is less dense; this holds for all concentrations. In addition, which ice forms first is dependent on the initial concentration of the solution. If it starts along the ethane liquidus (red line Fig 3C), ethane ice will form first, while the reverse is true for methane (blue line).

In order to measure the freezing point of the liquid solution between 60-70% nitrogen, we had to go to higher pressures to reach the dew point before the freezing point. By doing this, we encountered a strange phenomenon. At high pressure we find that the ternary creates two separate liquid phases (Fig 4A-B). Through spectroscopy we determined the bottom layer to be nitrogen rich, and the top layer to be ethane rich. We are further exploring at what pressures and temperatures these effects occur.

Understanding the freezing points of combinations of these species has implications for not only the lakes on the surface of Titan, but also for the evaporation/condensation/cloud cycle in the atmosphere, as well as the stability of these species on other outer solar system bodies. These results will help interpretation of future observational data, and guide current theoretical models.

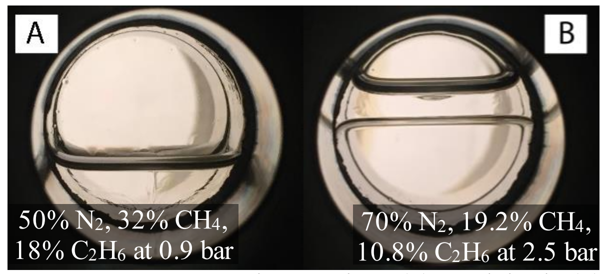

Figure 4. *Images taken at low (A) and high (B) pressure.*

Future Goals: The ices that can be created in the lab are useful to a variety of outer solar system bodies. For instance, mixtures of CO and N_2 are found on both Pluto and Triton, and spectral features acquired in the lab may aid in their identification [5]. We intend to continue to characterize the ternary of methane-ethane-nitrogen. We will also add other hydrocarbons and materials likely in Titan's atmosphere and surface to determine how their presence effects stability and spectral properties.

We would like to be able to study not only the spectroscopic properties of these materials at low temperatures, but the physical properties as well. These include density, viscosity, speed of sound, vapor pressure, refractive index, compressibility, thermal and electrical conductivity, and diffusion rates.

Computational modeling of the interactions of these species is underway and will provide parameters such as ΔH-vaporization, heat capacity (const. P), diffusion constant, static dielectric constant, thermal-expansion coefficient, isothermal compressibility, shear viscosity, hydrogen bond lifetime, melting points and bulk moduli.

Acknowledgments: This work was sponsored by a grant from the John and Maureen Hendricks Charitable Foundation, and NSF grant AST-1461200.

References: 1. Tegler S.C. et al. (2012) *The Astrophysical Journal*, *751*, 76. 2. Grundy W.M. et al. (2011) *Icarus*, *212*, 941-949. 3. Roe H.G. and Grundy W.M. (2012) *Icarus*, *219*, 733-736. 4. Protopapa S. et al. (2015) *Icarus*, *253*, 179-188. 5. Hanley J. et al. (2016) *LPSC*, Abstract #2438. 6. Prokhvatilov A. and Yantsevich L. (1983) *Sov. J. Low Temp. Phys., vol. 9, p. 94-98 (1983). 9*, 94-98.

IMPACT TOUGHNESS AND MOHS HARDNESS OF SIMPLE HYDROCARBON AND NITRILE ICES AT TITAN TEMPERATURES

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Introduction: Titan features many familiar terrestrial processes and landforms such as dunes and streambeds, but under exotic conditions (temperature, gravity, etc.) and with unfamiliar materials. Titan materials may include water ice, as well as photochemically-derived complex organics of arbitrarily high molecular weight ("tholins") may be rather hard. Because Titan has a hydrological cycle involving methane, low molecular weight organics such as benzene, alkanes, and acetonitrile could form bulk solid deposits by being dissolved by rainfall and precipitating as evaporites in dried-out lake beds, e.g. [1]. Many of these compounds are liquids at room temperature and are used as solvents. Here we freeze these materials and test their impact hardness with a view to providing a basis for interpreting Titan's geomorphology by analogy with the hardness of terrestrial rocks.

The presence of rounded cobbles at the Huygens landing site, and in 100-km-long streambeds [2], suggests that some Titan materials may be tough but somewhat ductile – deforming plastically rather than breaking in a brittle manner.

Test Methodology: We froze ~150ml cylindrical samples of standard laboratory solvents in liquid nitrogen. To obtain a semiquantitative measure of hardness (specifically the Young's modulus) we impacted the samples with an impulse hammer or penetrometer apparatus. This device (Figure 2) has a weighted ~10cm arm that is raised to a fixed stop and falls under gravity onto the sample: this measurement takes only seconds to perform, so can be performed at laboratory temperatures before the sample has time to warm up. A spherical indentor (a 12.7mm diameter steel ball bearing) on the underside of the arm impacts the sample, and the impact load pulse is recorded by a piezoelectric accelerometer (Endevco 2255) on the arm, the signal (typically a 0.5ms pulse) being recorded by a portable digital storage oscilloscope. The pulse height, indicating the peak deceleration, is proportional to $E^{2/5}$, where E is the Young's modulus. Relative results are indicated in Figure 1. Additionally, we performed some simple scratch tests, analogous to the Mohs hardness test familiar to field geologists, and report some simple observations.

Observations : The frozen texture of many of these materials was distinctive – see Figure 2. We did not anneal our water ice samples, thus they were typically crazed with cracks from expansion during freezing. As has been observed before, frozen ammonia solution looked glassy, with regular polygonal cracks at a spacing of roughly 1cm. All the hydrocarbons and nitriles studied formed white solids, sometimes waxy in appearance. Methanol was more transparent, with ~2-3mm wide needle-like crystals.

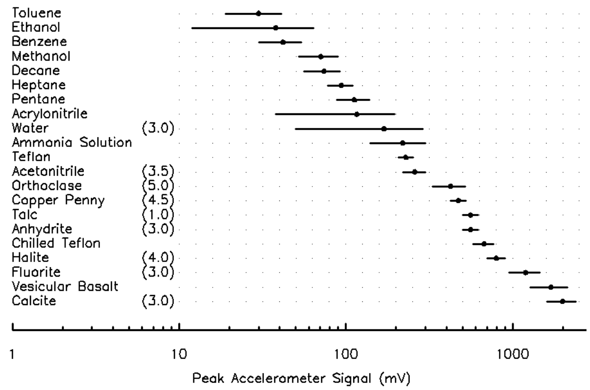

Figure 1: Results showing the relative impact hardness of materials (softest at the left). Bars show variation among typically ~5 tests: the Mohs scale values for known materials are listed in parentheses.

We did not conduct any experiments in this campaign on condensed gases, but we record here the observation that in preparing hydrogen cyanide for a previous spectroscopic study, at ~80K it has mechanical properties resembling those of stiff molasses. While acetonitrile has a Young's modulus that is modest compared with hard terrestrial rocks such as basalt, we noted that it is more or less impossible to crush bulk acetonitrile in a mortar and pestle (whereas the 'harder' rocks are straightforward to grind up with some effort). This presumably reflects the different measures of strength – acetonitrile is hard enough to resist elastic or plastic deformation under pestle loads, but does not fracture as easily as stiffer materials. In this connection, we have separately cast a small (4cm diameter, 1 cm thick) ingot of phenanthrene (a polycyclic aromatic hydrocarbon $C_{14}H_{10}$: this three-ring compound arguably may be somewhat representative of Titan's dune-forming materials). This slab (formed by melting granules at 375K) after immersion in liquid nitrogen could be scratched by water ice, and could be easily crushed by a pestle. Paraffin wax similarly cast became opaque and very brittle in liquid nitrogen - readily crumbling when agitated by a magnetic stirrer.

Results: Because the organic ices would melt on contact, comparison materials had to be chilled for scratching. We therefore also established that the Mohs hardness of comparison ('terrestrial') materials chilled to liquid nitrogen temperatures were the same as for room temperature (the ratio of ambient temperature to melting point being low in either case). We found that acetonitrile can be scratched by a steel knife blade, and by apatite (5). Cold fluorite (4) and acetonitrile can scratch each other. Acetonitrile can scratch cold calcite (3), but not a copper penny (3.5). These slightly discrepant data suggest a Mohs hardness of 3 to 4 for acetonitrile. Water ice can be scratched by a knife blade, fluorite and even a fingernail, suggesting a hardness of 2 or less. Separately, we obtained a small sample of tholin (pieces of a brittle orange film, about 0.7cm long, and less than 1mm thick) but it proved impossible to perform a scratch test without fracturing it.

It is notable that acetonitrile was appreciably tougher than ice (Figure 1). The alkanes and aromatics behaved as waxy, plastic solids, and were rather soft. All the ices investigated were colorless or white. Given the observed dark colour of Titan's sand seas, it is likely they are a more complex, carbon-rich composition.

Conclusions: Our macro-scale results are broadly consistent with recent nanoscale indentation experiments [3] which showed that tholin had a hardness and Young's modulus about an order of magnitude smaller than quartz sand and similar to gypsum; compounds intermediate in molecular weight between our frozen solvents and tholin, e.g. naphthalene and phenanthrene, had a hardness about an order of magnitude lower than tholin. While the materials studied so far are soft indeed compared with many terrestrial rocks, it should be remembered that the driving energies behind processes on Titan are commensurately smaller, owing to the low temperature and solar flux available, and the lower gravity. The generation of a similar landscape on Titan to that of the earth can therefore be understood, but is no less wonderful.

References: [1] Cordier, D., et al. (2016) Icarus, 270, 41 [2] Le Gall, A., et al. (2010) Icarus, 207, 948 [3] Yu, X. et al. (2018) LPSC IL Abstract 1786.

Acknowledgements: This work was supported by the Cassini project. We thank Neal Pearson for lab assistance.

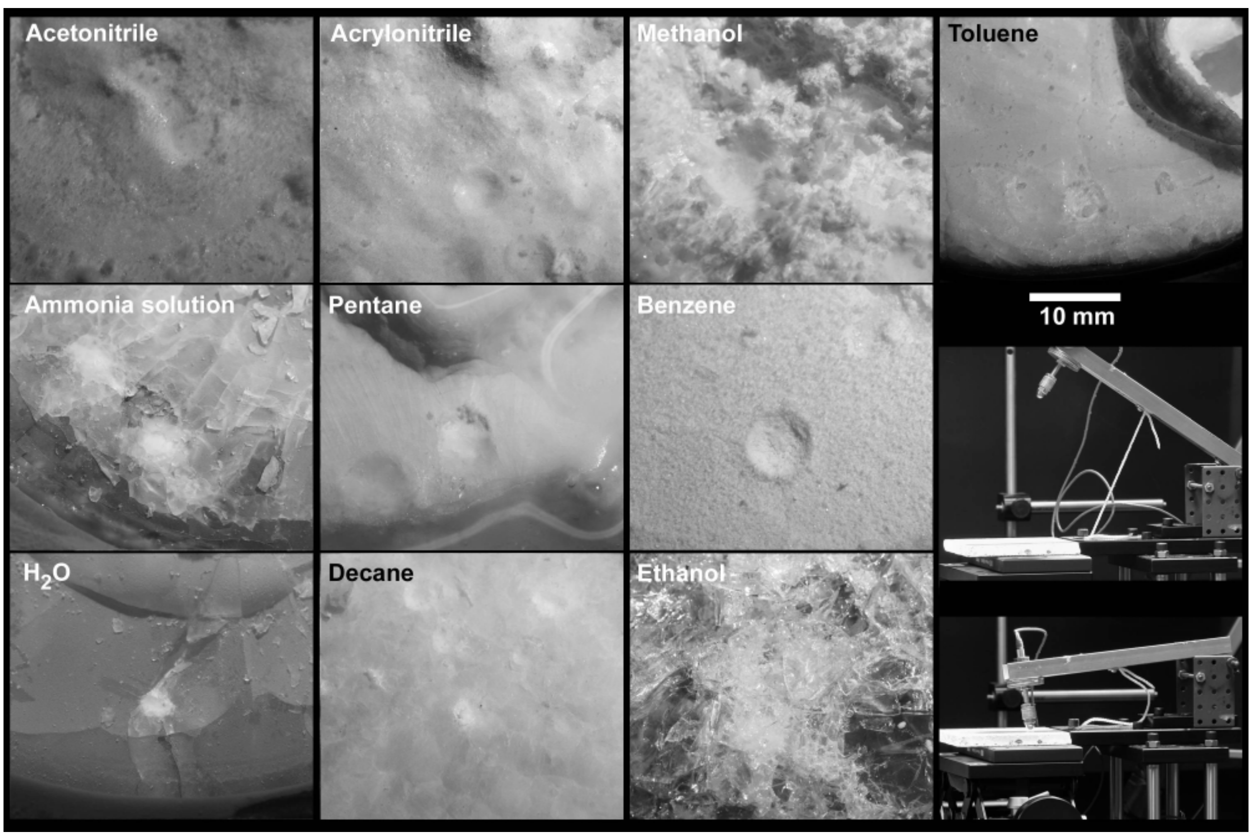

Figure 2: The different textures of the materials tested. The indenter apparatus is seen at lower right (not at the same scale as the closeup textures to which the scale bar applies). Alkanes, benzene and toluene appear waxy and deform rather plastically; the nitriles were appreciably harder. Water and water-ammonia ices experienced brittle failure, as did the alcohols.

GENERATION AND DETECTABILITY OF ORGANIC COMPOUNDS AND CO_2 FROM HYPERVELOCITY DUST IMPACTS INTO ICY SURFACES IN THE LAB. T. Munsat[1] , Z. Ulibarri[1], B. Abel[3], R. Dee[1], D. James[1,2], S. Kempf[1,2], Z. Kupihar[4], and Z. Sternovsky[1,2], [1]SSERVI Institute for Modeling Plasma, Atmospheres, and Cosmic Dust, University of Colorado (3400 Marine St., Boulder, CO 80303; munsat@colorado.edu), [2]Laboratory for Atmospheric and Space Physics University of Colorado, Boulder, CO, [3]Leibniz Institute of Surface Engineering,[4]Dept. of Chemistry & Biochemistry, Univ. Colorado, Boulder CO.

Although ice is prevalent in the solar system and the long-term evolution of many airless icy bodies is affected by hypervelocity micrometeoroid bombardment, there has been little experimental investigation into these impact phenomena, especially at the impact speeds seen on airless icy bodies or in fly-by spacecraft.

For example, CO_2 has been observed on various moons of Jupiter, Saturn, and Uranus, and is typically thought to have been native to these bodies or brought as C atoms from exogenic sources that are later converted to CO_2 by UV or charged particle irradiation. However, carbonaceous dust particles impacting into water ice may be an important production mechanism for CO_2 on these airless bodies.

As another example, laser ablation and light-gas gun experiments simulating dust impacts in the lab have successfully created amino acid precursors from base components in ice surfaces, indicating that dust impacts may be a mechanism for creating complex organic molecules necessary for life, but this has yet to be achieved with actual dust impacts.

Furthermore, there have been no experiments to date that use actual dust impacts to determine the survivability and detectability of complex organic chemicals by impact ionization, the mechanism used in time-of-flight mass spectrometers on fly-by spacecraft, such as the upcoming SUDA instrument on the Europa Clipper.

With the creation of a cryogenically cooled ice target for the dust accelerator facility at the NASA SSERVI Institute for Modeling Plasma, Atmospheres, and Cosmic Dust (IMPACT), it is now possible to study the effects of micrometeoroid impacts in a controlled environment under conditions relevant to airless icy bodies and fly-by spacecraft. Ice surfaces are prepared either by vapor deposition or by flash-freezing an aqueous solution of desired composition. Iron or carbonaceous dust is accelerated to 3-50 km/s and impacted onto the surface.

Time-of-flight mass spectra of the dust impact ejecta show that amino acids and even the more fragile di-peptide amino acid chains frozen into water ice can survive impact and be detected. Future experiments will probe characteristic fragmentation patterns that can be used to identify amino acids even after breakup.

Other experiments using trace amounts of CO_2 in water ice show that the CO_2 can be detected and that dust impacts covert some of this CO_2 to volatile CO. Upcoming experiments will investigate CO_2 production rates from carbonaceous dust impactors into water ice, and following experiments will probe the creation of more complex organic chemistry.

Results from recent and ongoing investigations will be presented.

Benefits of Virtual Reality for Mental Health in Long-Term Space Exploration. Z. Schauer[1,2], R. Witiw[1,2], A. Mardon[2,3], [1]MacEwan University (10700 104 Ave NW, Edmonton, AB T5J 4S2, schauerz@mymacewan.ca), [2]Antarctic Institute of Canada (103 11919 82 St NW, Edmonton, AB T5B 2W4, aamardon@yahoo.ca), [3]University of Alberta, (116 St & 85 Ave NW, Edmonton, AB T6G 2R3, Canada, aamardon@yahoo.ca).

Introduction: In this paper, it is argued that Virtual Reality [VR] has immense practical applications in fighting against fundamental mental health issues in long-term space exploration that develop in isolated, confined, and extreme [ICE] environments. Additionally, this paper will explore problems with VR as a solution to mental health issues in long-term space exploration and possible resolutions to these challenges.

In specific, this paper considers NASA's 2016 evidence report on the risk of cognitive or behavioural conditions and psychiatric disorders, and responds directly to the issues of mood disorders, neurasthenia, psychosomatic reactions, sleep, and cognitive functioning. Additionally, VR can provide psychiatric monitoring, exercise, continual and updated training, and sensory stimulation to fight monotony and boredom [1]. Further, VR can assist in psychosocial adaptation by supplying cooperative and leisurely activities for crews to play together to maintain team morale and unity while relieving stress and tension between members. "Sandbox" games, i.e. open-world games in which players have creative control over their environment and the objects around them, are discussed as a possibility to fight against the lack of space, autonomy, and privacy experienced by astronauts without overcrowding shuttle spaces. The use of artificial intelligence [AI] in VR Mars exploration training provides continuous practice with randomized scenarios to help astronauts retain their training over long-term space travel and to prepare for possible emergencies that require a quick improvised response.

Problems of Long-Term Space Exploration: In 2016 Nasa released an evidence report on the risk of adverse cognitive or behavioral conditions and psychiatric disorders for space-flight with the specific consideration of long-term space travel. NASA claimed they had two main issues in regards to mental health. First, inimical cognitive and/or behavioural conditions will occur within crew members and affect both the mental health of the crew and their performance. Second, they recognized a risk of crews developing mental health problems or disorders as a result of these adverse conditions if the conditions are not detected and diminished.

The Behavioural Health and Performance [BHP] element of NASA's Human Research Program [HRP] focused on managing three risks to performance and health encountered in ICE environments. First, managing problems faced due to sleep loss, circadian desynchronization, and work overload. Second, dealing with issues in performance and behaviour caused by improper cooperation, coordination, communication, and/or psychosocial adaptation within a team. Finally, mitigating the risk of adverse cognitive or behavioural conditions and psychiatric disorders.

NASA defines behavioural conditions as any "decrement in mood, cognition, morale, or interpersonal interaction that adversely affects operational readiness or performance." ICE environmental factors that long-term space exploration entails can result in adverse behaviour or cognitive symptoms, and further mental disorders can develop if these symptoms are left unchecked. Behavioural medicine training for the International Space Station [ISS] typifies three main mental, i.e. behavioural and cognitive, disorders encountered in long-term duration: delirium, adjustment disorder, and neurasthenia. All other behavioural conditions and psychiatric disorders are categorized as "any other psychiatric disorder," and are the first indications of a preexisting mental disorder that is possibly worsened or triggered by the stress of long-term space travel [1].

According to NASA, behavioural issues occur at a rate of approximately one per every 2.87 person-years, while incidents that could trigger adverse cognitive or behavioural symptoms occur at a rate of approximately one every 2.5 person-years [1]. However, as they note, these incidents are more likely to occur the longer astronauts are in flight. Furthermore, mood disorders, such as anxiety, PTSD, insomnia, and depression can develop without warning in healthy individuals. The risk of developing or ignoring behavioural, cognitive, and psychiatric conditions and disorders runs the risk of compromising mission success and further damaging the mental health of travellers.

The report mentions the possibility of incurring psychosomatic issues, which are physical manifestations of distress caused by or substantively influenced by emotional factors and neurasthenia, which they defined as "a nervous or mental weakness manifesting itself in tiredness…and quick loss of strength, low sensation threshold, extremely unstable moods, and sleep disturbance" [1]. Nasa does remind that the phenomena are under-studied empirically, but they also claim that neurasthenia does not often manifest until after four months of space travel. Since the phenomenon is one of the most reported issues in cosmonauts, and long-term space travel, especially to Mars, will undoubtedly extend well beyond that length, there is an increased need to address this issue for researchers.

Isolated and confined environments (ICE) are a fundamental issue in dealing with mental health amongst astronauts and most other mental health issues faced by astronauts are linked or affected by ICE environments. ICE environments cause behavioural problems, such as anger, anxiety, interpersonal conflict, social withdrawal, sleep deprivation, a decrease in group cohesion, and a drop in motivation, through a lack of variety in social interaction, leisure activities, and physical movement. These factors contribute to perceptions of monotony and lead to boredom, interpersonal conflict, loss of energy and concentration, and a decrease in physical activity and social interaction [118].

Furthermore, external medical help will be unavailable in long-term exploration when communication with earth takes hours and can only be done via messages. This added isolation requires that cosmonauts can adapt to new and developing issues in all aspects of their mission, including mental health. Although pilots have a degree in handling mental health issues, they may not have strong backgrounds in mental health and may face the same psychological issues as any other crew member, which could compromise their ability to recognize and respond correctly to troubling developments. When mental health issues like neurasthenia manifest, astronauts must be able to perform therapeutic tasks, such as exercise and entertainment.

NASA also reported those with eudaimonic well-being, i.e. well-being of personal satisfaction beyond hedonistic pleasure and avoidance of pain, are more likely to be autonomous and "thus the very nature of exploration missions will necessitate increased crew autonomy… thereby bolstering eudaimonic well-being" [1]. In addition, eudaimonic well-being includes finding the work one is doing meaningful, and that repetitive, mundane tasks compromise that feeling of meaning. Monotonous tasks may be more frequent than those that are meaningful during long-term exploration missions, and if something compelling isn't occupying the crew, their eudaimonic well-being may go down. In fact, NASA reported that without a variety of social interaction, leisure activities, and physical environment, astronauts could consequently experience monotony and result in boredom, interpersonal conflict, energy and concentration loss, and a lack of physical exercise and social interaction [1].

Researchers have reported that increased autonomy for astronauts can negatively affect motivation and performance, and yet also astronauts desire and, in one case, have famously taken a stand for increased independence by shutting down communications with mission control [2]. However, since shuttle sizes on extended missions, specifically to Mars, will be smaller, and the travel time will be much longer than regular space missions, monotony, boredom, decreased autonomy, such conditions may intensify eudaimonic well-being. Typical solutions like reading novels, photographing Earth, or allowing astronauts autonomy ("breathing room") can only go so far, and eudaimonic well-being may not sustain through this arduous mental period.

Salutogenic experiences, i.e. experiences that provide a sense of coherence and enduring positivity, associated with space travel, such as photographing the Earth are one of the most meaningful activities for astronauts, but this respite will no longer be available in extended length missions wherein the earth is out of view. Consequently, travellers spend months with the possibility of having no salutogenic experiences.

Virtual reality will be able to target these issues specifically, and how they manifest in each particular cosmonaut as VR "simulations are limited only by processing power and creativity" [3]. "Sandbox" type games, i.e. games in which the player is given the ability to create their own environments and manipulate it autonomously according to their own preferences, reflects the infinite capabilities of VR and will help deal with the common demand of astronauts for as much autonomy as possible without having repercussions on the mission.

References: [1] Slack, K. J. (2016) *Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders*. [2] Alfano, C. A. (2018) *Acta Astronautica*, 142, 289-299. [3] Salamon, N. (2018) *Acta Astronautica*, 146, 117-122.

DRILLING INTO TITAN CRYOGENIC MATERIALS : WATER-AMMONIA ICE AND PARAFFIN WAX

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Introduction: The determination of Titan's surface composition was recognized as a likely pressing post-Cassini scientific priority at that world, even in the late 1990s [1], and remains a central objective in Ocean Worlds exploration [2]. Of particular astrobiological interest [3,4] is material where Titan's abundant photochemical organics (nitriles, PAHS and other hydrocarbons) have interacted with liquid water, in impact melt sheets or cryovolcanic flows. In such environments, laboratory experiments have shown that important biology-relevant compounds such as amino acids and pyrimidines can be generated, and will be preserved once these environments freeze. To assess the extent of this prebiotic chemistry, it will be necessary to ingest Titan surface material into sensitive chemical instrumentation, requiring sample acquisition and transfer. While Titan also has sediments (notably in sand dunes and streambeds) sampling of bulk solid targets will require a drill or similar system to generate cuttings which can be ingested using a pneumatic sample transfer system [5]. Supported by the NASA COLDTECH program, we have begun testing drill operations (figure 1) into candidate Titan materials at Titan temperatures to verify that suitable cuttings are generated.

Target Materials: As for other outer planet satellites, the dominant crustal material on Titan is expected to be water ice, which behaves mechanically at 94K like rocks on Earth. For cryolava flows, the expected material would be the water-ammonia peritectic (lowest-melting-temperature mixture), which melts at 176K and has a composition of ~30% NH_3. This water-ammonia ice has thermal and mechanical properties which differ from pure water ice [6]. A wide range of organic materials are present on Titan, and indeed appear to dominate the observable surface. Although these likely are in complex refractory mixtures ("tholins"), Titan's methane hydrological cycle may form evaporite deposits (analogous to salt or gypsum deposits on Earth) of simple compounds (e.g. paraffins such as butane [7]). For these initial tests, a paraffin wax that is solid at room temperature (Sigma-Aldrich, melting temperature 58-62^{o}C per ASTM D87) was used for convenience, and to permit comparison with room temperature tests of the same material.

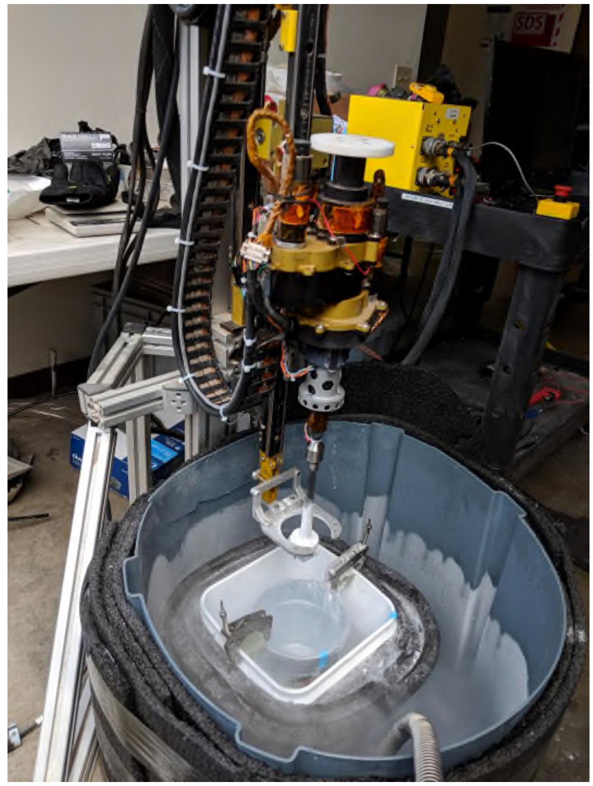

Figure 1: Test set-up at Honeybee's Pasadena facility. A rotary-percussive drill (black/gold) drives a custom bit (white, surrounded by a stabilization foot) into a ~2l sample container which is maintained below 100K by a liquid nitrogen bath. Outside this is a basin (blue) which retains a cold dry nitrogen atmosphere above the sample, preventing atmospheric moisture from freezing onto the sample or drill bit.

Test and Results: Water and ammonia solution were frozen to make their respective ices ; for the organic target, paraffin wax blocks were melted and then frozen to form a monolithic sample. Once samples were cooled by liquid nitrogen at 77 K, the Honeybee LITA (Life In The Atacama) rotary-percussive drill [8] was used with a dedicated bit (figure 2) advanced at 2 mm/s or less with a total (auger plus percussion) power of 50-60 W. The bit is conical to ensure it can always be withdrawn safely.

The first result is simply that of drill success : in all three materials tested, the drill generated cuttings and no seizing occurred. The specific energy for both water ice and water-ammonia ice was the same (~0.005 Whr/cc), while the paraffin wax had a value about 2x higher.

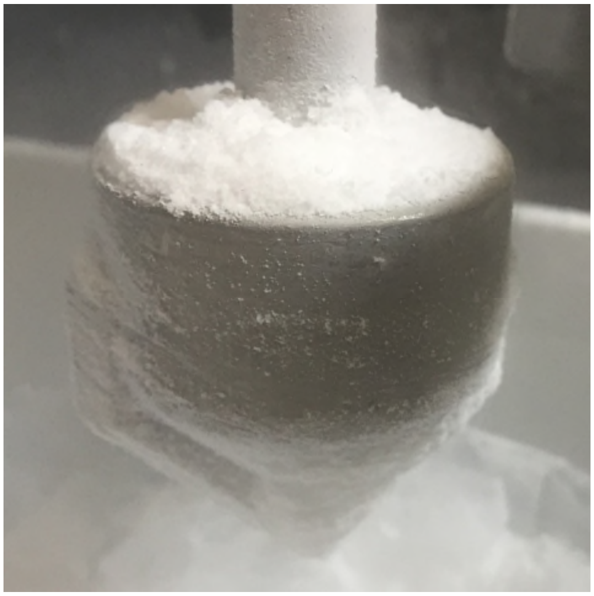

Figure 2: Close-up of the DRACO bit (DRill for the Acquisition of Complex Organics), 46mm in diameter, after drilling into frozen 30% ammonia solution (~ammonia dihydrate) ice at sub-100K temperatures. Satisfactory fine cuttings are generated.

Cuttings: Careful measures were taken to prevent condensation of moisture onto the sample cuttings, which were evaluated by an chilled inclined teflon plane to estimate friction coefficient and were visually inspected to assess particle size and shape. The materials tested generated more or less equant particles (i.e. no long 'swarf'). The water ice target generated fine powder, while the ammonia-water seemed to have a wider particle size range, with a number of larger chunks and aggregate particles, but many fine particles were also present. The paraffin wax (figure 3) interestingly had a prominent modal size fraction of 2-3 mm, the reason for which is not yet understood (it may be intrinsic to the material/temperature combination, or to the drill geometry, or both). Some fine particles were also present, however.

The water ice and water-ammonia cuttings had similar slip angles ; a steeper angle was required for the paraffin wax cuttings to slide, suggesting a higher cohesion/adhesion.

Figure 3: Close-up of the rotary-percussive cuttings from paraffin wax drilled at near 77K. Interestingly, a distinct 2-3mm particle size fraction dominates, although some finer particles exist

Conclusions: We have demonstrated that a rotary-percussive drill yields cuttings of Titan materials at Titan temperatures. The cuttings including fine material that can be ingested pneumatically. Further experiments are underway to evaluate different drill procedures (e.g. rotary-only) and different materials and temperatures.

References: [1] Chyba, C. et al. (1999) LPSC XX, Abstract #1537 [2] Lunine, J.I., 2017. Ocean worlds exploration. Acta Astronautica, 131, 123-130 [3] Thompson W. R. and Sagan C. (1992) Organic chemistry on Titan: Surface interactions, Symposium on Titan, ESA SP-338, 167-176. [4] Neish, C.D. et al., (2018). Strategies for Detecting Biological Molecules on Titan. Astrobiology, 18(5), 571-585. [5] Zacny, K. et al. (2017) LPSC XLVIII Abstract #1336 [6] Lorenz, R.D. and Shandera, S.E. (2001). Physical properties of ammonia-rich ice: Application to Titan. Geophysical Research Letters, 28(2), 215-218. [7] Cordier, D., et al. (2016) Structure of Titan's evaporites. Icarus, 270, 41-56. [8] Zacny, K. et al. (2014) LPSC XLV Abstract #1174.

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EXPLORING THE HABITABILITY OF ICY WORLDS THROUGH IMPACT IONIZATION MASS SPECTROSCOPY OF ICY DUST PARTICLES. Z. Sternovsky,[1,2] M. DeLuca,[1,2] Z. Kupihar,[3] B. Abel,[4] S. Kempf,[1,5] T. Munsat,[5] F. Postberg,[6] Z. Ulibarri[5], , [1] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, [2] Smead Aerospace Eng. Sci. Department, Univ. of Colorado, Boulder, CO 80309, [3] Biochemistry Department, University of Colorado, Boulder CO, [4] Leibniz Institute of Surface Modification, Leipzig, Germany, [5] Physics Department, University of Colorado, Boulder CO, [6] Institute of Earth Sciences, University of Heidelberg, Heidelberg, Germany**.** (Z. Sternovksy, LASP/University of Colorado, 1234 Innovation Drv. Boulder, CO 80303, Zoltan.Sternovsky@colorado.edu).

The astrobiological relevance of the Ocean Worlds – Enceladus and Europa in particular – is outstanding, as they possess liquid oceans that are in contact with a rocky core, where hydrothermal activity is assumed. Similar environments on Earth have been discovered to harbor unique and complex living ecosystems. There are natural processes that deliver samples of the surface ice and subsurface liquid ocean from these bodies to altitudes, where they become available for in situ detection and analysis using mass spectrometry techniques after the impact ionization of the icy dust particles. This detection method is demonstrated to provide sensitivity to organic and inorganic compounds solvated in the water ice and thus is a promising tool that is yet to be fully exploited. As of today, there are no existing laboratory capabilities for accelerating icy dust particles to typical velocities encountered in space (approx. 4 km/s). A design of a new facility has been completed that exploits a commercial electrospray source and a linear accelerator configuration to produce small, highly charged icy dust particle, and accelerate them to relevant velocities. Such capability is needed for high-fidelity studies of the impact ionization process of micron and submicron sized particles, as it would help to lay the foundations of the detectability of diverse biomarker molecules through impact ionization. Of particular interest is the investigation of the detectability of organic molecules embedded in icy grains, and the constraints on the sensitivity posed by absolute and relative concentrations, ionization efficiencies, and the effects of the geochemical environment, e.g. salt concentrations, and pH values. In addition, a reflectron time-of-flight (TOF) mass analyzer is under development that is specifically designed for application in the dust accelerator facility. In this case, the impact target is a cryogenically cooled icy sample of astrobiological relevance and the composition of ions generated by the impact of solid particles (e.g., iron) is measured. The TOF analyzer is designed to allow dust impacts in the normal direction, and for achieving high sensitivity and mass resolution.

PREPARING INTERPLANETARY PROBES FOR LONG-TERM POST-MISSION DATA COLECTION.

L. W. Tombrowski[1] and A. A. Mardon[1], [1] Antarctic Institute of Canada (aamardon@yahoo.ca).

Introduction: Future missions involving outer space probes must be designed with the concept of collecting scientific data for as long as possible. Applying this goal allows probes to continue transmitting data even after the probe's primary mission parameters are fulfilled. For example, after fulfilling its primary mission objective of a close flyby of Pluto, the interplanetary probe New Horizons was approved to extend its mission to explore objects in the Kuiper belt. While this mission extension was only put into effect after the completion of its primary objective, it illustrates how useful a probe can be even beyond achieving its primary goals. This abstract aims to briefly discuss some of the benefits and factors in preparing a probe for long-term exploration and data collection.

Potential Benefits: Deep space data not only aids current research but may also function as a useful source of reference in future research. Similar to how climate data collected hundreds of years ago now provides insight into trends such as climate change, data collected in deep space may provide useful insight into as-of-yet-undiscovered deep space trends and anomalies. [1] This is especially true for close observations of planets and moons within the solar system. Preparing for long-term data collection also allows researchers to get the most use possible out of each individual probe mission. Probe launches are expensive and require massive amounts of resources and manpower, both before and after launch. Therefore, it follows that each probe should be designed to provide useful data for as long as possible.

Preparation: There are multiple crucial steps in preparing a probe for a long-term mission. Naturally, in order to collect data for as long as possible in outer space, a probe needs to have a powerful and long-lasting source of energy. In the outer reaches of the solar system, solar energy is not a viable source of long-term energy. Therefore, nuclear batteries are used instead. The instrumentation and transmitters aboard the probe must also be designed to last as long as possible. Probe designers must also take into account the fact that a probe may take years or decades to arrive at the outer reaches of the solar system, at which point the sensors and computer systems aboard the probe will very likely have become out-of-date or even antiquated. A probe should therefore be outfitted with the most advanced and precise instrumentation possible, though this may be restricted by budget.

Rovers: The base principle of extending a probe's lifetime to collect additional data can also be applied to rovers sent to other planets and moons in the solar system. Even after a rover is unable to move around the planet's surface any longer, it can still collect data on the planet's climate and atmosphere. For planets closer to the Sun such as Mercury, Venus, and Mars, solar energy also becomes on an option for long-term power, though it is not as feasible for celestial bodies beyond the asteroid belt.

Difficulties: As has been stated previously, launches can be very costly without including the additional resources required to maintain the probe for an extended period of time. All deep space probe missions require manpower on Earth to monitor the probe constantly.

References: [1] Brohan B. et al. (2006) *Journal of Geophysical Research: Atmospheres, 111*, D12

DELVING INTO OCEAN WORLD INTERIORS. S. D. Vance[1], J. M. Brown[2], O. Bollengier[2], B. Journaux[2], E. H. Abramson[2], G. Shaw[3], M. Malaska[1] [1]Jet Propulsion Laboratory, California Institute of Technology (svance@jpl.nasa.gov), [2]Dept. of Earth and Space Science University of Washington, Seattle, [3]Union College, Schenectady.

Introduction: The workings and potential habitability of icy ocean worlds depends critically on the properties of their interiors, but spacecraft missions cannot directly measure these. Inferring the compositions and mechanical and thermal properties requires a combination of remote sensing and geophysical measurements. The field of possible solutions to the resulting inverse problem can be reduced by imposing prior knowledge in the form of structural models built from material properties obtained in the laboratory [1]. We are conducting multiple experiments at laboratories at the Mineral Physics Lab at the University of Washington, the Under Pressure Lab the Jet Propulsion Laboratory, and at labs at Union College. We provide highlights from those ongoing experiments, including detailed descriptions of the experimental apparatus, and applications to icy ocean worlds.

Equations of State for Oceans in Icy Worlds: To advance the state of the art for modeling the chemistry and dynamics of very deep and cold oceans that may have exotic compositions, we are advancing the state of the art for thermodynamic equations of state for pressures up to and exceeding 1 GPa, and over a broad range of temperatures. This work has necessitated the application of geophysical inverse modeling technique [2]. The input data are primarily sound speeds. We measure these below 1 GPa by measuring the time of flight of acoustic pulses, with an accuracy of better than 100 ppm. Above 1 GPa, we incorporate Brillouin measurements by other groups, and conduct impulsive stimulated scattering measurements in diamond anvil cells. High-pressure ice equations of state and thermodynamic properties are being extracted from newly measured in-situ single crystal synchrotron X-Ray diffraction experiments. The derived ice chemical potentials allow us to predict melting point depression due to various solutes, of all the ice phases that are predicted in icy ocean worlds and hypothetical watery super Earths (i.e. ice Ih, III, V, VI and VII). Those are also compared with newly measured melting point depression data obtained in the (Na,Cl,Mg,SO_4,NH_3)-H_2O system in diamond anvil cell high pressure apparatus.

Ices: The likelihood of high pressure water ice in the interiors of large icy satellites of the outer planets has renewed interest in the properties of high pressure polymorphs for modeling of these bodies. The 30-year old data that exists on ice polymorphs is probably not precise or accurate enough for quality modeling. A recent collaboration between the Geology and Physics Departments at Union College is aimed at producing high precision data on ice polymorphs up to 700 MPa and temperatures to about -30C. We are currently building the pressure vessel assembly to allow these measurements using ultrasonic interferometry. While construction is in progress we are testing the ultrasonic technique using long buffer rods. We hope to begin measurements by autumn of 2018.

In addition to the measurements in water ice, we are planning precision ultrasonic measurements on solid salts thought to be important as dissolved components of brines in the interiors of ice objects. These data should allow high precision thermodynamic analysis of complex brines in conjunction with previous (and ongoing) precision measurements on various brine solutions in progress at the University of Washington.

It is conceivable, though not as yet planned, that the equipment under development could be used for studies of clathrates and other solid phases incorporating various volatiles at elevated pressure and low temperatures. It is also possible that some aspects of these measurements could be extended to significantly higher pressures.

References: [1] Vance, S. D. et al.. (2017) *JGR,* 122*,* 10.1002/2017JE005341. [2] Brown, J. M. (2018) *Fluid Phase Equilibria* 463, 18-31.

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RHEOLOGICAL INVESTIGATION OF CRYOVOLCANIC SLURRIES. Alan G. Whittington[1], Aaron A. Morrison[1], Fang Zhong[2], Karl L. Mitchell[2], and Elizabeth M. Carey[2], [1]Department of Geological Sciences, University of Missouri, Columbia MO (whittingtona@missouri.edu), [2]Jet Propulsion Laboratory-Caltech, Pasadena CA.

Cryovolcanic processes have been considered theoretically for decades but with few experimental studies providing supporting data over a narrow compositional range. The rheology of these materials is fundamental in determining how cryovolcanic features are emplaced and the morphologies that result. We will attempt to address this knowledge gap by conducting a rheological investigation of briny crystal-liquid suspensions likely to be erupted on icy bodies. The few previous studies measuring subliquidus viscosity are plotted in Figure 1.

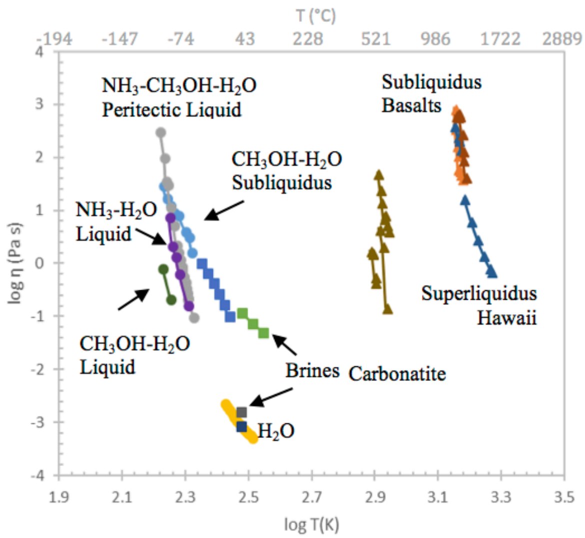

Figure 1. Viscosity data for water [1], brines [2,3], ammonia-water [4], methanol-water [4,5], ammonia-methanol-water [4], East African Rift basalts [6], Hawaiian basalt [7].

Brine compositions can be generated from an ammonia-water/ice source by partial melting, and then modified by crystal fractionation. Cryomagmas have been interpreted to form both dome or flow features, and potential cryogenic compositions span a similar viscosity range to that of silicate lavas. Many bodies exhibit flow features/constructs and a defined rheology will allow inferences about possible compositions based on observed morphology. This would be particularly useful on bodies, like Titan, Triton, or Pluto, that have atmospheres or geysers that can cover other features in (methane) frost or ejecta complicating spectral analysis of the feature itself. Understanding how these materials move, deform, and evolve upon crystallizing will help constrain what morphological features can form by various compositions.

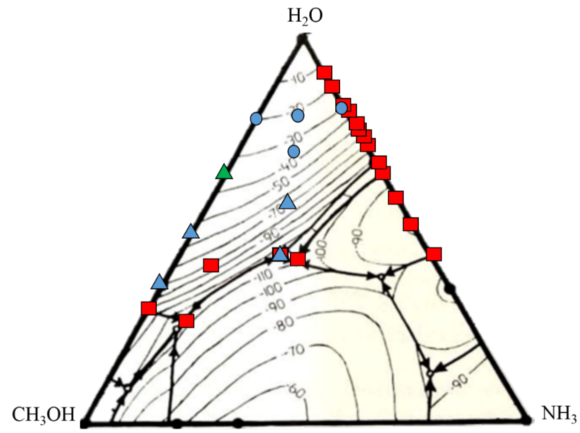

Figure 2. Water-ammonia-methanol ternary diagram (in wt.%) with liquidus isotherms (in ˚C), modified from [4]. Blue markers represent compositions proposed for detailed study. Compositions used in previous experimental studies shown by red squares [4] and green triangle [5].

The rheological data will allow comparisons to terrestrial silicates and determinations of how similarly the two kinds of materials behave. If they are, in fact, analogous to silicate systems (in terms of viscosity, flow index, yield strength, etc.), are they formed and emplaced by the same mechanisms and processes? And if not, what factors are contributing to the differences? Determining rheological properties of these cryogenic materials should allow us to answer these questions. Understanding these flows will also provide insight into the past and present evolution of various outer solar system bodies.

References: [1] J. Kestin et al. (1978) J. Phys. Chem. Ref. Data 7, 941–948. [2] H. Ozbek et al. (1977) Am. Chem. Soc. 29th Southeast Reg. Meet. [3] H. L. Zhang et al. (1997) J. Chem. Eng. Data 42, 526–530. [4] J. S. Kargel et al. (1991) Icarus 89, 93–112. [5] F. Zhong et al. (2009) Icarus 202, 607–619. [6] A. A. Morrison (2016) Master's Thesis, Univ. Missouri 74. [7] A. Sehlke et al. (2014) Bull. Volc. 76, 876.

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