Program and Abstract Volume

LPI Contribution No. 1774

LUNAR AND PLANETARY INSTITUTE

USRA

Workshop on The Habitability of Icy Worlds

February 5-7, 2014 • Pasadena, California

Sponsor

Universities Space Research Association
National Aeronautics and Space Administration

Conveners

David Senske
Jet Propulsion Laboratory, California Institute of Technology

Patricia Beauchamp
Jet Propulsion Laboratory, California Institute of Technology

Scientific Organizing Committee

David Senske
Jet Propulsion Laboratory, California Institute of Technology

Geoff Collins
Wheaton College

Olivier Grasset
Université de Nantes

Kevin Hand
Jet Propulsion Laboratory, California Institute of Technology

Chris McKay
Ames Research Center

Carolyn Porco
Space Science Institute

Louise Prockter
Applied Physics Laboratory, Johns Hopkins University

Linda Spilker
Jet Propulsion Laboratory, California Institute of Technology

Mary Voytek
National Aeronautics and Space Administration

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

LPI Contribution No. 1774

Compiled in 2014 by

Meeting and Publication Services
Lunar and Planetary Institute
USRA Houston
3600 Bay Area Boulevard, Houston TX 77058-1113

This material is based upon work supported by NASA under Award No. NNX08AC28A. Any opinions, findings, and conclusions or recommendations expressed in this volume are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

The Lunar and Planetary Institute is operated by the Universities Space Research Association under a cooperative agreement with the Science Mission Directorate of the National Aeronautics and Space Administration.

Abstracts in this volume may be cited as

Author A. B. (2013) Title of abstract. In *Workshop on the Habitability of Icy Worlds,* p. XX. LPI Contribution No. 1774, Lunar and Planetary Institute, Houston.

ISSN No. 0161-5297

Preface

This volume contains abstracts that have been accepted for presentation at the Workshop on the Habitability of Icy Worlds, February 5–7, 2014, Pasadena, California.

Administration and publications support for this meeting were provided by the staff of the Meeting and Publication Services Department at the Lunar and Planetary Institute.

Technical Guide to Sessions

Wednesday, February 5, 2014

8:15 a.m.	Madera Room	Overview of Icy Worlds
1:00 p.m.	Madera Room	Water and Exotic Solvents
3:15 p.m.	Madera Room	Organics and Their Detection
5:30 p.m.	San Marino	Poster Session
		Chemical Energy for Life on Icy Worlds
		Continuing and Future Outer Solar System Exploration
		Icy World Activity and Habitability Over Time
		Ocean Physics and Chemistry
		Organic Detection, Chemistry, and Laboratory Instruments

Thursday, February 6, 2014

8:30 a.m.	Madera Room	Chemical Energy for Life on Icy Worlds
9:45 a.m.	Madera Room	Ocean Physics and Chemistry
2:00 p.m.	Madera Room	Icy World Activity and Habitability Over Time
5:30 p.m.	San Marino	Poster Session Continued

Friday, February 7, 2014

8:30 a.m.	Madera Room	Continuing and Future Outer Solar System Exploration

Contents

Program xiii

Titan's Gravitational Field Inferred from Six Cassini Flybys
J. D. Anderson and G. Schubert 1

Finding New Icy Worlds: The Outer Solar System Origins Survey
M. T. Bannister, J. J. Kavelaars, B. Gladman, J. M. Petit, S. Gwyn, and OSSOS Collaboration 2

Fuel Cell Simulations of Geochemical Energetics on Rocky/Icy Worlds
L. M. Barge, P. Chellamuthu, and I. Kanik 3

Flyby Sounding of Europa's Icy Shell: Radar Investigations, Analogs, and Instruments for the Europa Clipper Mission
D. D. Blankenship, A. Moussessian, D. M. Schroeder, K. M. Soderlund, C. Grima, Y. Gim, J. J. Plaut,and B. E. Schmidt 4

The H_2O-$MGSO_4$ System and the Perspective of Deep Oceans for Large Icy Moons
O. Bollengier, O. Grasset, E. Le Menn, and G. Tobie 5

Hydrogen in Enceladus' Plume — Native or Artifact?
T. G. Brockwell, J. D. Walker, S. Chocron, J. H. Waite, R. S. Perryman, and B. A. Magee 6

Surface Texture as a Clue to what Lies Beneath Icy Worlds
B. J. Buratti 7

Hydrocarbon Trapping in Titan Surface Materials
M. L. Cable, T. Vu, M. Choukroun, C. Markus, R. Hodyss, and P. Beauchamp 8

A Comparative Analysis of Microbial Diversity in Spacecraft Assembly Facilities and Epsomite Lakes
F. Chen, M. La Duc, P. Vaishampayan, A. Probst, M. Schneegurt, and B. Clark 9

Effect of Ammonia on the Stability of Clathrate Hydrates: Experimental Study
M. Choukroun, T. Vu, E. Gloesener, A. Ibourichene, W. Smythe, M. Barmatz, and R. Hodyss 10

The Geophysical "No-Man's Land" of Transport Across Ice Shells
G. C. Collins, A. C. Barr, and R. M. Lopes 11

Icy World Transport Processes and Planetary Protection
C. Conley 12

Jovian Magnetospheric Impacts on Determination of Europa's Astrobiological Potential
J. F. Cooper and E. C. Sittler 13

Heat Transfer from a Shallow Water Sill on Europa — Habitable Zone?
K. L. Craft, G. W. Patterson, and R. P. Lowell 14

Double Ridges on Europa Accommodate Some of the Missing Surface Contraction
C. Culha, A. G. Hayes, M. Manga, and A. Thomas 15

The Effect of Rayleigh-Taylor Instabilities on the Thickness of Undifferentiated Crust on Kuiper Belt Objects
S. J. Desch, M. E. Rubin, and M. Neveu 16

How Quickly Does Drifting Material Traverse Through Europa's Ocean?
R. Farber and J. C. Goodman 17

Bioluminescence: A Potentially Convergent Signature of Life in Future Exploration of Europa's Subsurface Ocean
C. L. Flores Martinez 18

The H Chondrite Halite Parent Body: Warm, Wet, Organic-Rich, Rather Habitable and Possibly Ceres
M. Fries, S. Messenger, A. Steele, and M. Zolensky 19

Surfaces and Exospheres of the Icy Galilean Moons — An Integral Approach
A. Galli, A. Vorburger, P. Wurz, M. Tulej, N. Thomas, O. Mousis, S. Barabash, M. Wieser, and H. Lammer 20

Terrestrial Analogs for Detection and Characterization of Outflow from Potentially Habitable Zones Within Ice Shells of Icy Worlds
D. F. Gleeson 21

Structure and Dynamics of Ganymede: Implications for its Potential Habitability
O. Grasset 22

Europa Landing Site Selection Supported by Ice Penetrating Radar
C. Grima, D. M. Schroeder, D. D. Blankenship, and D. A. Young 23

Survival and Chemistry of Organics on the Near Surface of Europa and Titan
M. S. Gudipati, A. Lignell, I. Li Barnett, I. Couturier-Tamburelli, R. Jacovi, B. Fleury, and N. Carrasco 24

Spectra of Low-Temperature Chlorine Salt Hydrates and Implications for Europa
J. Hanley, J. B. Dalton III, V. F. Chevrier, and C. S. Jamieson 25

Triton — Warm Plumes or Cold Jets?
C. J. Hansen, F. Nimmo, J. Spencer, and H. Hammel 26

Techniques for the In Situ Analysis of Titan Lake Fluids
R. Hodyss, M. J. Malaska, and P. M. Beauchamp 27

Silica Nanoparticles Provide Evidence for Hydrothermal Activities at Enceladus
H.-W. Hsu, F. Postberg, Y. Sekine, S. Kempf, M. Horanyi, A. Juhasz, and R. Srama 28

Local Topographic Shielding and Radiation Shadows from Electron Irradiation on Europa
T. A. Hurford, J. F. Cooper, C. Paranicas, R. Greenberg, and S. J. Sturner 29

Water Production and Transport in the Ice Shell of Europa
K. Kalousova, G. Tobie, O. Soucek, G. Choblet, and O. Cadek 30

Subduction on Europa: A Nutrient Conveyor Belt into the Ice Shell?
S. A. Kattenhorn and L. M. Prockter 31

Compositional Mapping of Europa's Surface with a Dust Mass Spectrometer
S. Kempf, N. Altobelli, C. Briois, T. Cassidy, E. Grün, M. Horanyi, F. Postberg, J. Schmidt, S. Shasharina, R. Srama, and Z. Sternovsky 32

Characterizing Europa's Subsurface Water Ocean from Future Electromagnetic Induction Studies
K. K. Khurana, V. Angelopoulos, M. G. Kivelson, and C. T. Russell 33

Enceladus Remote Organic Detection: Aerogel Ice Particle Collection and In Situ Mass Spectrometer Analysis
J. P. Kirby, S. M. Jones, P. A. Willis, M. S. Anderson, and A. G. Davies 34

Towards an Astrobiological Vision for the Outer Solar System: The Europa and Enceladus Explorer Mission Designs
K. Konstantinidis, C. L. Flores Martinez, M. Hildebrandt, and R. Förstner 35

Experimental Facilities to Synthesize and Study Clathrate Hydrates: Applications to Icy Moons
E. Le Menn, D. Nna Mvondo, L. Bezacier, O. Bollengier, O. Grasset, and G. Tobie 36

Investigating the Habitability of Ceres
J.-Y. Li, M. V. Sykes, A. V. Pathare, J. P. Kirby, and J. C. Castillo-Rogez 37

The Astrobiology of Titan
J. I. Lunine 38

Composition and Dynamics of Titan's Lakes
A. LuspayKuti, V. F. Chevrier, S. Singh, A. Wagner, E. G. Rivera-Valentin, and F. C. Wasiak 39

Transport and Concentration of Organic Molecules on Titan-Like Worlds
M. J. Malaska, R. Hodyss, M. L. Cable, M. Choukroun, T. Vu, J. W. Barnes, and S. MacKenzie 40

Habitability and Composition at Europa
M. McGrath, W. B. McKinnon, J. H. Waite, T. Brockwell, D. Wyrick, and O. Mousis 41

Living on the Edge: The Habitability of Triton and Other Large Kuiper Belt Objects
W. B. McKinnon 42

PRIDE — Passive Radio Ice Depth Experiment — An Instrument to Measure Outer Planet Lunar Ice Depths from Orbit Using Neutrinos
T. C. Miller, S. Kleinfelder, S. Barwick, D. Besson, A. Connolly, G. W. Patterson, A. Romero-Wolf, R. Schaefer, and H. B. Sequeira 43

Progressive Climate Change on Titan: Implications for Habitability
J. M. Moore and A. D. Howard 44

Enceladus' Fully Cracked Core: Implications for Habitability
M. Neveu, C. R. Glein, A. D. Anbar, C. P. McKay, S. J. Desch, J. C. Castillo-Rogez, and P. Tsou 45

Laboratory Infrared Spectroscopy of Titan's Tholins in Liquid Methane and Liquid Ethane: Can Complex Organics in Titan's Lakes be Detected?
D. Nna-Mvondo, S. Singh, D. Mège, V. F. Chevrier, G. Tobie, and C. P. McKay 46

Spectroscopy, Photochemistry, and Viability of Bacillus Subtilis Spores After UV Irradiation: Implications for Survival and Detection at Europa
A. C. Noell, T. Ely, D. Bolser, H. Darrach, R. Hodyss, P. V. Johnson, and A. Ponce 47

Compartmentalisation Strategies for Hydrocarbon-Based Biota on Titan
L. H. Norman, A. D. Fortes, I. Crawford, and N. Skipper 48

Acetylene Fermentation: Relevance to Primordial Biogeochemistry and the Search for Life in the Outer Solar System
R. S. Oremland, S. M. Baesman, and L. G. Miller 49

Europa
R. T. Pappalardo 50

Habitability of Enceladus: Planetary Conditions for Life
C. Parkinson 51

Analysis of Ridge Terrains on Enceladus and Europa
D. A. Patthoff, R. T. Pappalardo, C. Chilton, and P. C. Thomas 52

Stereo Topography and Subsurface Thermal Profiles on Icy Satellites
C. B. Phillips 53

Enceladus: Small Moon, Big Possibilities
C. Porco 54

The Role of Clathrate Hydrates in the (Bio)Geochemical Cycles of Essential Elements of Life in the Deep Environments Within the Icy Moons
O. Prieto-Ballesteros and V. Muñoz-Iglesias 55

Diapiric Dynamics: Bringing Aqueous Solutions to Europa's Surface
L. C. Quick 56

A Radiation Hard ASIC for Thermal Instrumentation on the Europa Clipper Mission
G. Quilligan, J. DuMonthier, I. Kleynor, R. Katz, B. Lakew, and S. Aslam 57

Galileo PPR Observations of Europa: Correlations of Thermophysical Properties with Exogenic and Endogenic Processes
J. A. Rathbun, J. R. Spencer, and C. J. A. Howett 58

Europa's Water Vapor Plumes: The Potential for Discovery with JUICE-UVS Observations
K. D. Retherford, L. Roth, J. Saur, G. R. Gladstone, F. Nimmo, M. A. McGrath, P. D. Feldman, D. F. Strobel, A. J. Steffl, T. K. Greathouse, J. R. Spencer, F. Bagenal, and L. N. Fletcher 59

Europa's Water Vapor Plumes: A Powerful Search Technique Using HST UV Aurora Observations
L. Roth, K. D. Retherford, J. Saur, D. F. Strobel, P. D. Feldman, M. A. McGrath, and F. Nimmo 61

The Drive to Life on Wet and Icy Worlds
M. J. Russell, L. M. Barge, and I. Kanik 62

Does Impact Crater Morphology, Global Topography and Color of an Icy Body Betray its Habitability?
P. Schenk 63

A Chaos Conveyor Belt?
B. E. Schmidt, B. Gooch, K. M. Soderlund, G. W. Patterson, C. C. Walker, P. M. Schenk, and D. D. Blankenship 64

Icy World Science and Habitability in the National Science Olympiad for Middle School Students
D. M. Schroeder, C. B. Burch, K. M. Soderlund, C. Grima, D. D. Blankenship, T. D. Komacek, T. M. Quinn, M. A. Van Hecke, B. E. Schmidt, G. W. Patterson, and J. J. Plaut 65

The Titan Aerosol Simulants Produced at Low Temperature in the Titan Haze Simulation Experiment at NASA Ames: A Closer Analog of Titan's Aerosols?
E. M. Sciamma-O'Brien, K. T. Upton, J. L. Beauchamp, and F. Salama 66

Investigating Icy World Habitability Through the Europa Clipper Mission Concept
D. A. Senske, R. T. Pappalardo, L. Prockter, S. Vance, W. Patterson, and Europa Study Team 67

Astrobiological Investigation of Pitch Lake, Trinidad, and its Potential as an Analog for Titan
J. N. Shivak and D. Schulze-Makuch....68

Two Geologic Constraints on Europa's Ice Shell Thickness and Implications for Habitability
K. N. Singer, W. B. McKinnon, and P. S. Schenk....69

Solubility of Organics in Liquid Hydrocarbons Under Titan Surface Conditions
S. Singh, V. F. Chevrier, M. Leitner, M. Gainor, and L. Roe....70

In Situ Plasma Measurements at the Galilean Moons Europa, Ganymede and Callisto
E. C. Sittler, J. F. Cooper, N. Paschalidis, and A. S. Lipatov....71

Convective Processes in Europa's Ocean and Their Implications for Ice-Ocean Coupling
K. M. Soderlund, B. E. Schmidt, J. Wicht, and D. D. Blankenship....72

Habitability Potential of Icy Moons: A Comparative Study
A. Solomonidou, A. Coustenis, Th. Encrenaz, F. Sohl, H. Hussmann, G. Bampasidis, F. W. Wagner, F. Raulin, D. Schulze-Makuch, and R. M. C. Lopes....73

Formation and Evolution of Titan's Organic Seas
C. Sotin, K. J. Lawrence, B. Seignovert, J. W. Barnes, R. H. Brown, K. H. Baines, B. J. Buratti, R. N. Clark, and P. D. Nicholson....74

Surface Dust Mass Analyzer for the Compositional Mapping of Icy Surfaces
Z. Sternovsky, S. Kempf, E. Gruen, M. Horanyi, and R. Srama....75

FT-IR Measurements of Cold Cross Sections of Hydrocarbons
K. Sung, G. C. Toon, and L. R. Brown....76

Prebiotic Chemistry on Cryogenic Worlds: Tribochemical Reactions of Organics and Water in Titan Dunes
D. A. Thomas and J. L. Beauchamp....77

JUICE: The ESA Mission to Study Habitability of the Jovian Icy Moons
D. Titov, S. Barabash, L. Bruzzone, M. Dougherty, L. Duvet, C. Erd, L. Fletcher, R. Gladstone, O. Grasset, L. Gurvits, P. Hartogh, H. Hussmann, L. Iess, R. Jaumann, Y. Langevin, P. Palumbo, G. Piccioni, and J.-E. Wahlund....78

Tidal and Rotational Signatures of Internal Oceans on Titan, Ganymede and Callisto
G. Tobie, R.-M. Baland, O. Bollengier, A. Lefevre, and G. Mitri....79

Formation and Evolution of an Internal Ocean on Titan
G. Tobie, O. Bollengier, A. Lefevre, N. Marounina, J. Monteux, R.-M. Baland, L. Bezacier, H. Amit, S. Carpy, G. Choblet, and O. Grasset....80

The Preservation of Organics and Brines in Low-Temperature Aqueous Glasses
J. D. Toner, D. C. Catling, and B. Light....81

Imaging Spectroscopy as a Key Technique to Constrain Habitability and Origins on Icy Worlds
F. Tosi, G. Piccioni, M. C. De Sanctis, F. Capaccioni, G. Filacchione, P. Cerroni, and M. T. Capria....82

Returning Samples from Icy Enceladus
P. Tsou, A. Ariel, D. Brownlee, J. Baross, D. Glavin, C. Glein, I. Kanik, and C. Mckay....83

Heat Generated by Ocean Tides in the Outer Solar System
R. Tyler....84

Thermodynamic Constraints on Ocean Structure and Water-Rock Chemistry in the Large Icy Satellites
S. Vance, J. M. Brown, C. Choukroun, and C. Sotin 85

Enceladus Plume Composition
J. H. Waite, T. Brockwell, W. S. Lewis, B. Magee, W. B. McKinnon, O. Mousis, and A. Bouquet 86

Energy Implications of Fragmentation Processes in Europa's Ice Shell
C. C. Walker and B. E. Schmidt 87

The Influence of Magnetospheric Plasma on Magnetic Sounding of Europa's Interior Oceans
J. H. Westlake, A. M. Rymer, J. C. Kasper, R. L. McNutt, M. L. Stevens, H. T. Smith, C. Parker, A. W. Case, G. C. Ho, and D. G. Mitchell 88

On Detectability of Amino Acids in the Plumes of Enceladus Using Far-Infrared Signatures
D. P. Winebrenner and M. H. Arbab 89

Thermophysical Modeling of the Megaregolith on Airless Bodies in the Outer Solar System: Implications for Oceans and Heat Flow Estimates
S. E. Wood, S. G. Griffiths, and J. Eluszkiewicz 90

Investigating the Formation, Evolution, and Habitability of the Galilean Satellites with High Performance Mass Spectrometry
D. Y. Wyrick, J. H. Waite, T. Brockwell, M. McGrath, W. B. McKinnon, O. Mousis, and B. Magee 91

Icy Satellite Surface Compositions from Thermal Infrared Spectroscopy
C. L. Young, J. J. Wray, R. N. Clark, K. P. Hand, and J. R. Spencer 92

Sample Tube Sealing and Sample Integrity Analysis for Future Sample Return Missions
P. Younse, K. Accord, D. Aveline, X. Bao, L. Beegle, D. Berisford, P. Bhandari, C. Budney, E. Chandler, F. Chen, N. Chen, M. Cooper, S. Chung, P. DeGrosse, E. Dodd, M. Fuller, D. Lewis, K. Lykens, M. Parker, and R. Smith 93

Big Impacts and Transient Oceans on Titan
K. J. Zahnle, D. G. Korycansky, and C. A. Nixon 94

Program

Wednesday, February 5, 2014
OVERVIEW OF ICY WORLDS
8:15 a.m. Madera Room

Chairs: **David Senske**
Pat Beauchamp

8:15 a.m. Senske D. * Beauchamp P. M. *
Welcome to the Workshop

8:30 a.m. Green J. L. *
NASA Update

8:45 a.m. Grasset O. *
Structure and Dynamics of Ganymede: Implications for its Potential Habitability **[#4011]**
Ganymede, the largest moon of the solar system, is of great relevance to astrobiological studies because it satisfies a large number or prerequisites for habitability. A review of its properties, especially regarding its habitability, will be given.

9:10 a.m. Pappalardo R. T. *
Europa **[#4060]**
Europa is an astrobiological and geophysical wonderland, and this presentation will review the key processes that appear to shape this ocean world.

9:35 a.m. Porco C. *
Enceladus: Small Moon, Big Possibilities **[#4090]**
Enceladus has become a major object of astrobiological interest as a result of nearly a decade's worth of high-powered spacecraft. In this presentation, I will review what we currently know about Enceladus that makes it a viable habitable icy world.

10:00 a.m. Lunine J. I. *
The Astrobiology of Titan **[#4065]**
Titan is a target of astrobiological interest because of its thick atmosphere, ample organics inventory, large size and presence of water ice and rock. Multiple habitable environments, or prebiotically interesting environments, may exist.

10:25 a.m. BREAK

10:40 a.m. McKinnon W. B. *
Living on the Edge: The Habitability of Triton and Other Large Kuiper Belt Objects **[#4061]**
Triton, with its more volatile- and organic-rich composition, deep ocean/ice layer, protective atmosphere, and likely history of "insane" tidal heating, offers a fascinating comparison with Europa in terms of habitability.

11:05 a.m. Conley C. *
Icy World Transport Processes and Planetary Protection **[#4095]**
Understanding micron-scale and larger subsurface transport processes in liquid-solid mixtures is important for assessing the risk, due to exploration, of contamination that could interfere with future scientific study.

11:30 a.m. DISCUSSION

11:45 a.m. LUNCH

Wednesday, February 5, 2014
WATER AND EXOTIC SOLVENTS
1:00 p.m. Madera Room

Chairs:	**Morgan Cable** **Michael Malaska**
1:00 p.m.	LuspayKuti A. * Chevrier V. F. Singh S. Wagner A. Rivera-Valentin E. G. Wasiak F. C. *Composition and Dynamics of Titan's Lakes* **[#4016]** We present laboratory evaporation rate measurements of pure methane and ethane, and methane-ethane mixtures under Titan surface conditions for a wide variety of compositions. Based on our results we approximate the ethane content of Ontario Lacus.
1:15 p.m.	Malaska M. J. * Hodyss R. Cable M. L. Choukroun M. Vu T. Barnes J. W. MacKenzie S. *Transport and Concentration of Organic Molecules on Titan-Like Worlds* **[#4020]** Organic fluids / moving molecules around / emplace deposits.
1:30 p.m.	Cable M. L. * Vu T. Choukroun M. Markus C. Hodyss R. Beauchamp P. *Hydrocarbon Trapping in Titan Surface Materials* **[#4024]** Benzene is found on Titan and is probably one of the most abundant evaporites to form around Titan lakes. We discovered trapping of ethane in crystalline benzene at 90 K, suggesting evaporite basins could act as hydrocarbon reservoirs on Titan.
1:45 p.m.	Nna-Mvondo D. * Singh S. Mège D. Chevrier V. F. Tobie G. McKay C. P. *Laboratory Infrared Spectroscopy of Titan's Tholins in Liquid Methane and Liquid Ethane: Can Complex Organics in Titan's Lakes be Detected?* **[#4018]** In this work, we present a Titan's lakes experimental simulation we have performed in order to examine the spectroscopic signature of a liquid methane and a liquid ethane in contact with laboratory analogs (tholins) of Titan's aerosols.
2:00 p.m.	Toner J. D. * Catling D. C. Light B. *The Preservation of Organics and Brines in Low-Temperature Aqueous Glasses* **[#4015]** Aqueous solutions can supercool and transition to a glass at low temperatures. Glasses would preserve brines and organics in a pristine state, and could be used to study the aqueous history and habitability of icy worlds.
2:15 p.m.	Hanley J. * Dalton III J. B. Chevrier V. F. Jamieson C. S. *Spectra of Low-Temperature Chlorine Salt Hydrates and Implications for Europa* **[#4082]** Low-temperature spectra of chloride and (per)chlorate salts exhibit diagnostic features that should allow for their detection, if present. Chlorine salts lower the activity of water, limiting potential life.
2:30 p.m.	DISCUSSION
3:00 p.m.	BREAK

Wednesday, February 5, 2014
ORGANICS AND THEIR DETECTION
3:15 p.m. Madera Room

Chairs: **Murthy Gudipati**
Christophe Sotin

3:15 p.m. Gudipati M. S. * Lignell A. Li Barnett I. Couturier-Tamburelli I. Jacovi R. Fleury B. Carrasco N.
Survival and Chemistry of Organics on the Near Surface of Europa and Titan **[#4086]**
Our interest in the context of habitability of icy worlds is of twofold: 1) whether the organics can survive radiation-rich surface of Europa, and 2) whether Titan can harvest photons into chemical energy in the lower atmosphere and on the surface.

3:30 p.m. Sciamma-O'Brien E. M. * Upton K. T. Beauchamp J. L. Salama F.
The Titan Aerosol Simulants Produced at Low Temperature in the Titan Haze Simulation Experiment at NASA Ames: A Closer Analog of Titan's Aerosols? **[#4019]**
The Titan Haze Simulation experiment simulates the first steps of Titan's atmospheric chemistry at low temperature and produces aerosols that are simpler than other lab experiments' and appear to be more representative of Titan's aerosols.

3:45 p.m. Singh S. * Chevrier V. F. Leitner M. Gainor M. Roe L.
Solubility of Organics in Liquid Hydrocarbons Under Titan Surface Conditions **[#4021]**
Solubility of acetylene and acetonitrile in liquid methane and ethane under Titan surface conditions. This will lead us to understand the composition of Titan lakes.

4:00 p.m. Thomas D. A. * Beauchamp J. L.
Prebiotic Chemistry on Cryogenic Worlds: Tribochemical Reactions of Organics and Water in Titan Dunes **[#4089]**
In this work, we postulate that the mechanical energy from wind-driven grains in the dunes of Titan can ultimately drive chemical processes and lead to the incorporation of oxygen into organic compounds via tribochemical reactions.

4:15 p.m. Sotin C. * Lawrence K. J. Seignovert B. Barnes J. W. Brown R. H. Baines K. H. Buratti B. J. Clark R. N. Nicholson P. D.
Formation and Evolution of Titan's Organic Seas **[#4057]**
The Cassini Solstice Mission provides an opportunity to witness the seasonal evolution of Titan's organic seas and their relationships with lakes and evaporite candidates in the southern and northern hemisphere.

4:30 p.m. Shivak J. N. * Schulze-Makuch D. **CANCELED**
Astrobiological Investigation of Pitch Lake, Trinidad, and its Potential as an Analog for Titan **[#4009]**
Located in Trinidad, Pitch Lake is a natural liquid asphalt lake. It is one of the best terrestrial analogs to the surface of Titan currently available for study on the Earth and should be the subject of targeted astrobiological investigations.

4:45 p.m. DISCUSSION

Wednesday, February 5, 2014
POSTER SESSION: CHEMICAL ENERGY FOR LIFE ON ICY WORLDS
5:30 p.m. San Marino

Norman L. H. Fortes A. D. Crawford I. Skipper N.
Compartmentalisation Strategies for Hydrocarbon-Based Biota on Titan **[#4002]**
Self-assembled structures in organic solvents is an under-developed research area and whether membranes could exist in the alkane lakes of Titan has remained an important, but unanswered, question. Therefore we are researching this possibility.

Russell M. J. Barge L. M. Kanik I.
The Drive to Life on Wet and Icy Worlds **[#4023]**
Life's onset on any abiotic rocky wet icy world resolves chemical and electrochemical disequilibria generated by serpentinizing systems.

Oremland R. S. Baesman S. M. Miller L. G.
Acetylene Fermentation: Relevance to Primordial Biogeochemistry and the Search for Life in the Outer Solar System **[#4003]**
Acetylene supports the growth of some terrestrial anaerobes. The reaction is highly exothermic. The abundance of acetylene in the methane-rich planet(oid)s of the outer solar system could represent a means of nourishment for resident alien microbes.

Wednesday, February 5, 2014
POSTER SESSION: CONTINUING AND FUTURE OUTER SOLAR SYSTEM EXPLORATION
5:30 p.m. San Marino

Hodyss R. Malaska M. J. Beauchamp P. M.
Techniques for the In Situ Analysis of Titan Lake Fluids **[#4010]**
Titan's lakes are a primary target for future Titan exploration. We present two successfully tested in situ methods to analyze Titan lake fluids: 1) fiber optic probes, and 2) solid phase micro-extraction (SPME) fibers for preconcentration of analytes.

Anderson J. D. Schubert G.
Titan's Gravitational Field Inferred from Six Cassini Flybys **[#4006]**
Titan's gravitational field is inferred from an analysis of archived radio Doppler data for six Cassini flybys. Results are consistent with a differentiated hydrostatic satellite. We find no determination of the tidal Love number k_2.

Khurana K. K. Angelopoulos V. Kivelson M. G. Russell C. T.
Characterizing Europa's Subsurface Water Ocean from Future Electromagnetic Induction Studies **[#4081]**
We propose future observation strategies and missions that exploit the multiple frequency character of Jupiter's magnetic field spectrum to infer key properties of Europa's subsurface ocean such as thickness, composition and location.

Sittler E. C. Jr. Cooper J. F. Paschalidis N. Lipatov A. S.
In Situ Plasma Measurements at the Galilean Moons Europa, Ganymede and Callisto **[#4027]**
We will present plasma measurements and their requirements at the Galilean moons with plasma package composed of Ion Mass Spectrometer (IMS), Electron Spectrometer (ELS) and Energetic Particle Detector (EPD).

Westlake J. H. Rymer A. M. Kasper J. C. McNutt R. L. Stevens M. L. Smith H. T. Parker C. Case A. W. Ho G. C. Mitchell D. G.
The Influence of Magnetospheric Plasma on Magnetic Sounding of Europa's Interior Oceans **[#4032]**
We discuss measurements of the Jovian and Europan plasma environments necessary for magnetic sounding of Europa's subsurface oceans. We introduce a suite of Faraday cup instrumentation that can provide these high quality plasma measurements.

Galli A. Vorburger A. Wurz P. Tulej M. Thomas N. Mousis O. Barabash S. Wieser M. Lammer H.
Surfaces and Exospheres of the Icy Galilean Moons — An Integral Approach **[#4017]**
We present an integral approach to characterize surfaces and exospheres of the icy Galilean moons in preparation for the JUICE mission to Jupiter. We combine new lab experiments with existing observations of exospheric species and numerical models.

Miller T. C. Kleinfelder S. Barwick S. Besson D. Connolly A. Patterson G. W. Romero-Wolf A. Schaefer R. Sequeira H. B.
PRIDE — Passive Radio Ice Depth Experiment — An Instrument to Measure Outer Planet Lunar Ice Depths from Orbit Using Neutrinos **[#4008]**
We describe a concept for a single instrument to measure the thickness of an ice shell, such as Europa's, by making use of the Askaryan Effect Radio Frequency signal from ultra high energy neutrinos.

Tosi F. Piccioni G. De Sanctis M. C. Capaccioni F. Filacchione G. Cerroni P. Capria M. T.
Imaging Spectroscopy as a Key Technique to Constrain Habitability and Origins on Icy Worlds **[#4030]**
In this paper we present some notable science cases where the imaging spectroscopy remote sensing technique will be crucial to constrain the potential habitability of several icy bodies that will be closely explored in the future.

Kempf S. Altobelli N. Briois C. Cassidy T. Grün E. Horanyi M. Postberg F. Schmidt J. Shasharina S. Srama R. Sternovsky Z.
Compositional Mapping of Europa's Surface with a Dust Mass Spectrometer **[#4052]**
We developed a detector to measure the composition Europa's dust exosphere. Because these grains are samples from Europa's surface, unique information will be obtained about the surface as well as geological activities on and below the surface.

Kirby J. P. Jones S. M. Willis P. A. Anderson M. S. Davies A. G.
Enceladus Remote Organic Detection: Aerogel Ice Particle Collection and In Situ Mass Spectrometer Analysis **[#4076]**
The Enceladus Amino Acid Sampler is designed for hypervelocity ice particle collection for in situ trace analysis of organics. It employs an aerogel matrix inlet to a mass spectrometer for organic detection, to mitigate alteration or fragmentation.

Flores Martinez C. L.
Bioluminescence: A Potentially Convergent Signature of Life in Future Exploration of Europa's Subsurface Ocean **[#4040]**
This presentation deals with theoretical and evolutionary aspects pertaining to the nature and degree of biological complexity that is expectable among putative organisms on Europa. Bioluminescence is suggested as a new type of biosignature.

Gleeson D. F.
Terrestrial Analogs for Detection and Characterization of Outflow from Potentially Habitable Zones Within Ice Shells of Icy Worlds **[#4051]**
Satellite detection and characterization of mineral deposits associated with supraglacial outflow allows remote characterization of subsurface icy habitats.

Sternovsky Z. Kempf S. Gruen E. Horanyi M. Srama R.
Surface Dust Mass Analyzer for the Compositional Mapping of Icy Surfaces **[#4069]**
SUDA is an instrument developed for future missions to measure the surface composition of airless satellites. The very sensitive method is based on mass-analyzing the dust particles ejected from the surface by micrometeoroid impacts.

Young C. L. Wray J. J. Clark R. N. Hand K. P. Spencer J. R.
Icy Satellite Surface Compositions from Thermal Infrared Spectroscopy **[#4038]**
We present an approach to average Cassini CIRS spectra from the full icy moon dataset to increase signal-to-noise and use emissivity spectra to constrain surface compositions. We take a first look at Iapetus and find a spectral feature in FP3.

Blankenship D. D. Moussessian A. Schroeder D. M. Soderlund K. M. Grima C. Gim Y. Plaut J. J. Schmidt B. E.
Flyby Sounding of Europa's Icy Shell: Radar Investigations, Analogs, and Instruments for the Europa Clipper Mission **[#4053]**
Radar investigations, analogs, and instruments for the Europa Clipper Mission.

Grima C. Schroeder D. M. Blankenship D. D. Young D. A.
Europa Landing Site Selection Supported by Ice Penetrating Radar **[#4046]**
We propose a novel radar sounder analysis technique to quantitatively characterize the surface roughness and permittivity of icy worlds at relevant scales for potential landing site selection. Demonstration is made over analog terrains in Antarctica.

Retherford K. D. Roth L. Saur J. Gladstone G. R. Nimmo F. McGrath M. A. Feldman P. D. Strobel D. F. Steffl A. J. Greathouse T. K. Spencer J. R. Bagenal F. Fletcher L. N.
Europa's Water Vapor Plumes: The Potential for Discovery with JUICE-UVS Observations **[#4033]**
Far-UV auroral imaging and stellar occultation techniques are able to identify whether water vapor plumes exist on Europa. Detailed observation plans for the JUICE Ultraviolet Spectrograph (UVS) are reported along with recent HST auroral imaging.

Quilligan G. DuMonthier J. Kleynor I. Katz R. Lakew B. Aslam S.
A Radiation Hard ASIC for Thermal Instrumentation on the Europa Clipper Mission **[#4066]**
We describe one key hardware development at Goddard that is undergoing maturation for risk mitigation, a radiation hardened by design (RHBD) multi-channel digitizer (MCD) Application Specific Integrated Circuit (ASIC) for thermopile array readout.

Younse P. Accord K. Aveline D. Bao X. Beegle L. Berisford D. Bhandari P. Budney C. Chandler E. Chen F. Chen N. Cooper M. Chung S. DeGrosse P. Dodd E. Fuller M. Lewis D. Lykens K. Parker M. Smith R.
Sample Tube Sealing and Sample Integrity Analysis for Future Sample Return Missions **[#4067]**
Four sealing methods were selected, along with a set of tests for characterization and evaluation of sample preservation capability for future sample return missions.

Schroeder D. M. Burch C. B. Soderlund K. M. Grima C. Blankenship D. D. Komacek T. D. Quinn T. M. Van Hecke M. A. Schmidt B. E. Patterson G. W. Plaut J. J.
Icy World Science and Habitability in the National Science Olympiad for Middle School Students **[#4005]**
We present a new competition for middles school students focused on icy world science and habitability as an opportunity for outreach.

Chen F. La Duc M. Vaishampayan P. Probst A. Schneegurt M. Clark B.
A Comparative Analysis of Microbial Diversity in Spacecraft Assembly Facilities and Epsomite Lakes **[#4093]**
We have studied the MgSO4 tolerance of microbes from spacecraft assembly facilities and epsomite lakes using both cultivation and cultivation-independent methods to investigate the potential of forward contamination of icy-moon exploration.

Li J.-Y. Sykes M. V. Pathare A. V. Kirby J. P. Castillo-Rogez J. C.
Investigating the Habitability of Ceres **[#4031]**
We review our current knowledge about Ceres' water regime, and discuss the key future investigations that will advance our understanding about the past and present habitability of Ceres.

Wednesday, February 5, 2014
POSTER SESSION: ICY WORLD ACTIVITY AND HABITABILITY OVER TIME
5:30 p.m. San Marino

Schenk P.
Does Impact Crater Morphology, Global Topography and Color of an Icy Body Betray its Habitability? **[#4091]**
The most habitable regions are essentially inaccessible. We must rely on indirect means to determine whether, a) they have an ocean, b) the ocean is close to the surface, and c) the inner "core," ocean and icy shell are geologically interacting.

Solomonidou A. Coustenis A. Encrenaz Th. Sohl F. Hussmann H. Bampasidis G. Wagner F. W. Raulin F. Schulze-Makuch D. Lopes R. M. C.
Habitability Potential of Icy Moons: A Comparative Study **[#4014]**
This research focuses on the environments of the outer solar system satellites such as Titan, Enceladus, Europa and Ganymede that seem to satisfy many of the "classical" criteria for habitability with promising conditions for the development of life.

Buratti B. J.
Surface Texture as a Clue to what Lies Beneath Icy Worlds **[#4048]**
Surface properties of icy worlds, including the porosity of the upper regolith and particle attributes such as size and shape, can provide markers for habitable environments.

Hurford T. A. Cooper J. F. Paranicas C. Greenberg R. Sturner S. J.
Local Topographic Shielding and Radiation Shadows from Electron Irradiation on Europa **[#4092]**
The high radiation of energy into Jupiter's surface makes it unlikely that simple organisms can survive on its surface and also drives chemical and physical processing of the surface.

Wood S. E. Griffiths S. G. Eluszkiewicz J.
Thermophysical Modeling of the Megaregolith on Airless Bodies in the Outer Solar System: Implications for Oceans and Heat Flow Estimates **[#4075]**
A theoretical and modeling study of the interactive and evolving relationships between physical properties, volatiles, and thermodynamic conditions in the deep regolith of large airless bodies of the outer solar system.

Rathbun J. A. Spencer J. R. Howett C. J. A.
Galileo PPR Observations of Europa: Correlations of Thermophysical Properties with Exogenic and Endogenic Processes **[#4045]**
We will determine Europa's surface thermophysical properties (thermal inertia and albedo) using Galileo PPR data. These properties will be correlated with geologic unit and exogenic processes.

Singer K. N. McKinnon W. B. Schenk P. S.
Two Geologic Constraints on Europa's Ice Shell Thickness and Implications for Habitability **[#4073]**
We present ice shell thickness estimates from two types of features on Europa: 1) circular-to-subcircular pits, uplifts, and small chaos regions and 2) ring graben around large impact basins. A 3 km (endmember minimum) ice shell is predicted.

Craft K. L. Patterson G. W. Lowell R. P.
Heat Transfer from a Shallow Water Sill on Europa — Habitable Zone? **[#4084]**
Sills on Europa may provide habitable zones on Europa.

Walker C. C. Schmidt B. E.
Energy Implications of Fragmentation Processes in Europa's Ice Shell **[#4054]**
We use fragmentation theory, commonly used in weapons/blast analysis, to study Europa's chaos terrain. We constrain the energy required within the ice shell for such features to form, as well as other material properties important for habitability.

Culha C. Hayes A. G. Manga M. Thomas A. CANCELED
Double Ridges on Europa Accommodate Some of the Missing Surface Contraction **[#4029]**
Here we use cross-cutting relationships between features such as bands and ridges on Jupiter's moon, Europa, to study surface deformation over large spatial scales.

Patthoff D. A. Pappalardo R. T. Chilton C. Thomas P. C.
Analysis of Ridge Terrains on Enceladus and Europa **[#4050]**
We classify the types of ridges on Enceladus, with the use of limb topography and traditional mapping techniques, and compare them to those on Europa to consider the implications for subsurface water and potential habitability.

Moore J. M. Howard A. D.
Progressive Climate Change on Titan: Implications for Habitability **[#4007]**
If Titan's present climate is a relatively modern development, then it provides an important test for the virility of life in the cosmos.

Le Menn E. Nna Mvondo D. Bezacier L. Bollengier O. Grasset O. Tobie G.
Experimental Facilities to Synthesize and Study Clathrate Hydrates: Applications to Icy Moons **[#4039]**
A series of experimental investigations are being carried out on mixed CH_4-N_2 and CH_4-CO_2 clathrate hydrates, compounds of high interest for icy moons. First results on their phase diagram and their infrared and Raman signatures will be presented.

Choukroun M. Vu T. Gloesener E. Ibourichene A. Smythe W. Barmatz M. Hodyss R.
Effect of Ammonia on the Stability of Clathrate Hydrates: Experimental Study **[#4049]**
We present new apparatus and results on the stability of clathrate hydrates of methane and tetrahydrofuran in presence of a variety of ammonia concentrations. These results have implications on potential outgassing processes on Titan.

Hansen C. J. Nimmo F. Spencer J. Hammel H.
Triton — Warm Plumes or Cold Jets? **[#4085]**
Are the plumes on Triton more analogous to Enceladus or Mars?

Cooper J. F. Sittler E. C.
Jovian Magnetospheric Impacts on Determination of Europa's Astrobiological Potential **[#4026]**
Astrobiological potential of Europa for potential habitability and life is governed by availability of liquid water, organic chemistry, and energy. Jovian magnetospheric interactions impact and can even enable surveys for these resources.

Wednesday, February 5, 2014
POSTER SESSION: OCEAN PHYSICS AND CHEMISTRY
5:30 p.m. San Marino

Brockwell T. G. Walker J. D. Chocron S. Waite J. H. Perryman R. S. Magee B. A.
Hydrogen in Enceladus' Plume — Native or Artifact? **[#4022]**
The H_2 abundance in the plumes of Enceladus is velocity dependent.Through a combination of impact physics and modeling of the physisorption and chemisorption within the INMS antechamber we attempt to find the proportion of native H_2 in the plume.

Tobie G. Baland R.-M. Bollengier O. Lefevre A. Mitri G.
Tidal and Rotational Signatures of Internal Oceans on Titan, Ganymede and Callisto **[#4044]**
Based on recent results on the tidal deformation and obliquity of Titan, we will predict tidal and rotational signatures of an internal ocean inside Ganymede and Callisto to be tested by the future ESA's JUICE mission.

Bollengier O. Grasset O. Le Menn E. Tobie G.
The H_2O-$MgSO_4$ System and the Perspective of Deep Oceans for Large Icy Moons **[#4036]**
We conducted new experiments in the H_2O-$MgSO_4$ system to explore the liquidus of H_2O ice phases over the 0–1 GPa pressure range. These results bring new constraints on the formation and stability of deep oceans in large icy moons.

Wednesday, February 5, 2014
POSTER SESSION: ORGANIC DETECTION, CHEMISTRY, AND LABORATORY INSTRUMENTS
5:30 p.m. San Marino

Noell A. C. Ely T. Bolser D. Darrach H. Hodyss R. Johnson P. V. Ponce A.
Spectroscopy, Photochemistry, and Viability of Bacillus Subtilis Spores After UV Irradiation: Implications for Survival and Detection at Europa **[#4088]**
UV irradiation studies of Bacillus subtilis and dipicolinic acid to investigate survival of microbes and organic molecules in the near surface environment of Europa.

Winebrenner D. P. Arbab M. H.
On Detectability of Amino Acids in the Plumes of Enceladus Using Far-Infrared Signatures **[#4080]**
We present new data on far-infrared resonances, such as might in principle be observed using the Cassini CIRS, of amino acids in crystalline form and frozen from aqueous solutions.

Sung K. Toon G. C. Brown L. R.
FT-IR Measurements of Cold Cross Sections of Hydrocarbons **[#4070]**
We discuss temperature dependent cross sections of hydrocarbons by analyzing laboratory spectra in two approaches; 1) direct measurements of the cold cross sections, 2) derivation of pseudolines by fitting the laboratory spectra simultaneously.

Wyrick D. Y. Waite J. H. Jr. Brockwell T. McGrath M. McKinnon W. B. Mousis O. Magee B.
Investigating the Formation, Evolution, and Habitability of the Galilean Satellites with High Performance Mass Spectrometry **[#4055]**
High performance mass spectrometry allows direct sampling and measurement of isotopic composition, present day volatile ratios, and the correct identification of complex organics, all essential to understanding Europa’s habitability.

McGrath M. McKinnon W. B. Waite J. H. Brockwell T. Wyrick D. Mousis O.
Habitability and Composition at Europa **[#4083]**
We discuss how compositional measurements bear directly on the issue of habitability, focusing on ocean chemistry and redox state.

Parkinson C.
Habitability of Enceladus: Planetary Conditions for Life **[#4094]**
The presence of a plume on Saturn’s moon Enceladus offers a unique opportunity to sample the interior composition of an icy satellite, to look for interesting chemistry and possible signs of life.

Barge L. M. Chellamuthu P. Kanik I.
Fuel Cell Simulations of Geochemical Energetics on Rocky/Icy Worlds **[#4025]**
Fuel cell experiments simulating the emergence of bioenergetics will not only be informative for the origin of life on Earth, but may help determine whether it is possible for life to have emerged in hydrothermal environments on icy worlds.

Thursday, February 6, 2014
CHEMICAL ENERGY FOR LIFE ON ICY WORLDS
8:30 a.m. Madera Room

Chairs: **Mary Voytek**
Kevin Hand

8:30 a.m. McKinnon W. B. *
Timescales and Geography for Exchange Processes

8:38 a.m. Soderlund K. M. *
Ocean Currents and Predictions for Thin Ice Regions

8:46 a.m. McCollom T. *
Models for the Europan Seafloor Reductant Flux

8:54 a.m. Hoehler T. *
Life on Earth as a Guide for Energy Limits on Other Worlds

9:02 a.m. PANEL DISCUSSION

Thursday, February 6, 2014
OCEAN PHYSICS AND CHEMISTRY
9:45 a.m. Madera Room

Chairs: **Steve Vance**
Mathieu Choukroun

9:45 a.m. Tyler R. *
Heat Generated by Ocean Tides in the Outer Solar System **[#4056]**
Resonantly forced energetic ocean tidal scenarios appear to stand in the way of an ocean attempting to freeze. The associated dissipative heat can stabilize oceans in such configurations, suggesting liquid oceans may be quite common in the universe.

10:00 a.m. Soderlund K. M. * Schmidt B. E. Wicht J. Blankenship D. D.
Convective Processes in Europa's Ocean and Their Implications for Ice-Ocean Coupling **[#4037]**
We use numerical simulations of rotating convection in a spherical shell to investigate Europa's ocean dynamics.

10:15 a.m. Tobie G. * Bollengier O. Lefevre A. Marounina N. Monteux J. Baland R.-M. Bezacier L. Amit H. Carpy S. Choblet G. Grasset O.
Formation and Evolution of an Internal Ocean on Titan **[#4041]**
In order to address the conditions under which the ocean formed and evolved throughout Titan's history, we combine different numerical and experimental approaches.

10:30 a.m. BREAK

10:45 a.m. Farber R. * Goodman J. C.
How Quickly does Drifting Material Traverse Through Europa's Ocean? **[#4059]**
We modeled vertical transport processes in Europa's ocean by inserting Lagrangian tracers into a simulated hydrothermal plume. Analysis of tracer motion suggests a transit time of ~1000 years for material to move between seafloor and ice shell.

11:00 a.m. Kalousova K. * Tobie G. Soucek O. Choblet G. Cadek O.
Water Production and Transport in the Ice Shell of Europa **[#4058]**
Tidal heating within Europa's interior might be strong enough to produce liquid water reservoirs at shallow depths. This study aims to determine the stability of these reservoirs and evaluate the importance of various water transport mechanisms.

11:15 a.m. Vance S. * Brown J. M. Choukroun C. Sotin C.
Thermodynamic Constraints on Ocean Structure and Water-Rock Chemistry in the Large Icy Satellites **[#4087]**
Water-rock interactions have typically been regarded as limited in larger ocean worlds like Ganymede and Titan due to dense ice phases V and VI that cover the rocky seafloor. We reassess this using new thermodynamic data for oceans and ices.

11:30 a.m. Prieto-Ballesteros O. * Muñoz-Iglesias V.
The Role of Clathrate Hydrates in the (Bio)Geochemical Cycles of Essential Elements of Life in the Deep Environments Within the Icy Moons **[#4077]**
Here we discuss the role of clathrate hydrates as major reservoirs for the essential chemical elements for life within the icy moons, and how these putative sources behave in salty solutions and at high pressure.

11:45 a.m. Waite J. H. Jr. * Brockwell T. Lewis W. S. Magee B. McKinnon W. B. Mousis O. Bouquet A.
Enceladus Plume Composition **[#4013]**
The talk will discuss the results of observations of the plume gas composition at Enceladus as carried out by the Cassini Ion Neutral Mass Spectrometer. Interpretations with regard to ocean chemistry will be discussed.

12:00 p.m. Hsu H.-W. * Postberg F. Sekine Y. Kempf S. Horanyi M. Juhasz A. Srama R.
Silica Nanoparticles Provide Evidence for Hydrothermal Activities at Enceladus **[#4042]**
The formation of nano-phase silica particles detected by Cassini severely limits possible evolution pathways for Enceladus by setting constraints on temperature, heat sources, and rock/water composition.

12:15 p.m. DISCUSSION

12:45 p.m. LUNCH

Thursday, February 6, 2014
ICY WORLD ACTIVITY AND HABITABILITY OVER TIME
2:00 p.m. Madera Room

Chairs: **Cynthia Phillips**
Simon Kattenhorn

2:00 p.m. Collins G. C. Barr A. C. Lopes R. M.
The Geophysical "No-Man's Land" of Transport Across Ice Shells **[#4071]**
Vertical transport processes across ice shells are important for questions of habitability and planetary protection. We present an inventory of processes, their applications to icy worlds of interest, and disconnects in the vertical transport chain.

2:15 p.m. Kattenhorn S. A. * Prockter L. M.
Subduction on Europa: A Nutrient Conveyor Belt into the Ice Shell? **[#4004]**
Portions of Europa's surface were removed along discrete tectonic boundaries that we hypothesize to be subduction zones. These zones may have moved chemical compounds important for astrobiological potential from the surface into the Europan interior.

2:30 p.m. Schmidt B. E. * Gooch B. Soderlund K. M. Patterson G. W. Walker C. C.
Schenk P. M. Blankenship D. D.
A Chaos Conveyor Belt? **[#4072]**
We evaluate the habitability of Europa's ice and ocean in light of active processes, including the lifetime of liquid reservoirs, vertical and horizontal material transport, and the resurfacing rate that may form and influence shallow habitats.

2:45 p.m. Quick L. C. *
Diapiric Dynamics: Bringing Aqueous Solutions to Europa's Surface **[#4062]**
This work seeks to place constraints on the conditions by which aqueous solutions and cryomagmatic melts may be bought to Europa's surface via diapiric ascent, based on dynamics and heat transfer.

3:00 p.m. Roth L. * Retherford K. D. Saur J. Strobel D. F. Feldman P. D.
McGrath M. A. Nimmo F.
Europa's Water Vapor Plumes: A Powerful Search Technique using HST UV Aurora Observations **[#4068]**
We present a technique to search for plumes on Europa using new STIS images of the UV aurora morphology obtained during two HST visits in November and December 2012.

3:15 p.m. BREAK

3:30 p.m. Fries M. * Messenger S. Steele A. Zolensky M.
The H Chondrite Halite Parent Body: Warm, Wet, Organic-Rich, Rather Habitable and Possibly Ceres **[#4078]**
Ancient halite grains are found in some H-chondrite meteorites, but these halites are exogenous to H chondrites. The original halite parent body (HaPB) must have been warm, wet, and organic-rich. The dwarf planet Ceres has been proposed as the HaPB.

3:45 p.m. Neveu M. * Glein C. R. Anbar A. D. McKay C. P. Desch S. J.
Castillo-Rogez J. C. Tsou P.
Enceladus' Fully Cracked Core: Implications for Habitability **[#4028]**
We model the geophysical evolution of Enceladus' core for 4.56 Gyr. The core is likely fully cracked and hydrated. A core and ocean in chemical equilibrium provide little redox energy, but present core temperatures are mild enough for thermophiles.

4:00 p.m. Desch S. J. * Rubin M. E. Neveu M.
The Effect of Rayleigh-Taylor Instabilities on the Thickness of Undifferentiated Crust on Kuiper Belt Objects **[#4074]**
We present new calculations of KBO evolution, showing that Rayleigh-Taylor instabilities do not lead to much overturn of undifferentiated ice/rock crusts with underlying ice mantles. The persistence of insulating crusts aids the retention of water.

4:15 p.m. Phillips C. B. *
Stereo Topography and Subsurface Thermal Profiles on Icy Satellites **[#4064]**
Stereo topography is used in combination with numerical modeling to study the subsurface structure and thermal history of icy satellites of Jupiter and Saturn, with important implications for past and perhaps current habitability.

4:30 p.m. Zahnle K. J. * Korycansky D. G. Nixon C. A.
Big Impacts and Transient Oceans on Titan **[#4063]**
We ask what happened to Titan after the impacts came. A nominal Menrva heats the surface to ~170 K; it takes heroic assumptions to reach 273 K. Bigger impacts (e.g., putative Hotei impact) produce meltwater oceans that last for decades or centuries.

4:45 p.m. DISCUSSION

5:30 p.m. POSTER SESSION CONTINUED

Friday, February 7, 2014
CONTINUING AND FUTURE OUTER SOLAR SYSTEM EXPLORATION
8:30 a.m. Madera Room

Chairs: **Linda Spilker**
Louise Prockter

8:30 a.m. Titov D. Barabash S. Bruzzone L. Dougherty M. Duvet L. Erd C. Fletcher L. Gladstone R. Grasset O. * Gurvits L. Hartogh P. Hussmann H. Iess L. Jaumann R. Langevin Y. Palumbo P. Piccioni G. Wahlund J.-E.
JUICE: The ESA Mission to Study Habitability of the Jovian Icy Moons **[#4035]**
The presentation will give an overview of the ESA's JUICE (JUpiter ICy moons Explorer) mission to the Jovian system, its science scenario, observation strategy, and the newly selected payload.

8:50 a.m. Senske D. A. * Pappalardo R. T. Prockter L. Vance S. Patterson W. Europa Study Team
Investigating Icy World Habitability Through the Europa Clipper Mission Concept **[#4012]**
Exploration of Europa via the Europa Clipper mission would provide a fundamental advancement in our understanding of icy world habitability.

9:10 a.m. Bannister M. T. * Kavelaars J. J. Gladman B. Petit J. M. Gwyn S. OSSOS Collaboration
Finding New Icy Worlds: The Outer Solar System Origins Survey **[#4079]**
How many icy worlds are there in the outer Solar System, and how many are there of each size? OSSOS, a survey of the trans-Neptunian region using CFHT, will provide a thousand new worlds with exquisitely characterised, high-precision orbits.

9:25 a.m. Konstantinidis K. * Flores Martinez C. L. Hildebrandt M. Förstner R.
Towards an Astrobiological Vision for the Outer Solar System: The Europa and Enceladus Explorer Mission Designs **[#4043]**
Two DLR funded projects to develop a submersible for Europa and a melting probe for Enceladus are presented. A lander mission concept is given. Instruments are proposed, assuming analogous traits for both biospheres.

9:40 a.m. DISCUSSION

9:55 a.m. BREAK

10:10 a.m. WORKSHOP DISCUSSION, FINDINGS, AND WRAP-UP

TITAN'S GRAVITATIONAL FIELD INFERRED FROM SIX CASSINI FLYBYS. John D. Anderson, *Jet Propulsion Laboratory (Retired), California Institute of Technology, Pasadena, California, USA*, Gerald Schubert, *Department of Earth and Space Sciences, University of California, Los Angeles, California, USA*.

Titan's gravitational field is inferred from an analysis of archived radio Doppler data for six Cassini flybys. The analysis considers each flyby separately in contrast to the approach of lumping all the data together in a massive inversion. In this way it is possible to gain an improved understanding of the character of each flyby and its usefulness in constraining the gravitational coefficient C_{22}. We find a best-fit value of C_{22} equal to $(12.84 \pm 0.18) \times 10^{-6}$, significantly larger than the value of 10.0×10^{-6} obtained from an inversion of the lumped Cassini data. We also find no determination of the tidal Love number k_2. The larger value of C_{22} implies a moment of inertia factor equal to 0.3776 ± 0.0021 and a less differentiated Titan than is suggested by the smaller value. While it is not possible to rule out either value of C_{22}, we prefer the larger value because its derivation results from a more hands on analysis of the data that extracts the weak hydrostatic signal while revealing the effects of gravity anomalies and unmodeled spacecraft accelerations on each of the six flybys.

FINDING NEW ICY WORLDS: THE OUTER SOLAR SYSTEM ORIGINS SURVEY.

M. T. Bannister[1,2], J. J. Kavelaars[1,2], B. Gladman[3], J. M. Petit[4], S. Gwyn[2], and the Outer Solar System Origins Survey Collaboration.

[1]micheleb@uvic.ca; University of Victoria, 3800 Finnerty Rd, Victoria, BC V8P 5C2, Canada, [2]NRC-Herzberg, 5071 West Saanich Rd, Victoria, BC V9E 2E7, Canada, [3]University of British Columbia, Vancouver, BC, Canada, [4]Observatoire de Besançon, Université de Franche Comté – CNRS, Institut UTINAM, 41 bis avenue de l'Observatoire, 25010 Besançon Cedex, France.

Introduction: Great progress has been made in the last decade in understanding the origins of the population of small icy objects in the outer Solar System. The sculpting of their orbits under the architectural rearrangement of the giant planets has left its signature in these small-body populations. The discoveries have shown an essential need for surveys that collect samples of the population to have full understanding of their intrinsic observational biases, so that the underlying population may correctly be retrieved. The existing known sample of well-characterised trans-Neptunian objects are too few to make progress in distinguishing between models of the history of the Solar System.

Survey: We have designed a survey using 560 hours of CFHT time over four years to provide on the order of a thousand new TNOs with exquisitely characterised, high-precision orbits. This new survey began observations in February 2013, and by its conclusion in 2016 will have doubled the number of trans-Neptunian objects available for testing models.

We target areas of sky placed to sample the dynamically cold and the dynamically hot populations (Fig. 1), imaging to a survey depth of m_r ~ 24.5, which allows us to sample the Kuiper belt across the full range of sizes produced by accretion and collisional processing in the original planetesimal belt.

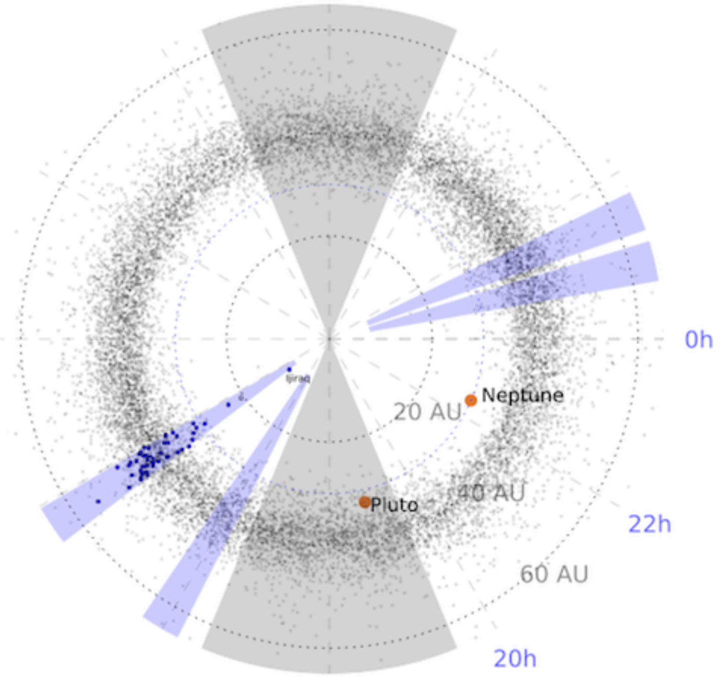


Figure 1. The four 2013 target survey areas (blue cones) as seen projected on the plane of the Solar System; sensitivity extends to ~300 AU (truncated here for graphical purposes). Dark blue dots indicate OSSOS discoveries; open blue circles discoveries that have not yet been recovered but will be during the dedicated follow-up year of observations in 2014. Grey dots are the CFEPS L7 model of the Kuiper belt [1]; grey cones are the areas of observation avoidance of the galactic plane.

Four more target survey areas will be added in 2015, also targeting objects in orbital resonances with Neptune.

References: [1] Petit, J. M. et al. (2011) *AJ, 142(4)*, 131.

FUEL CELL SIMULATIONS OF GEOCHEMICAL ENERGETICS ON ROCKY / ICY WORLDS. L. M. Barge[1], P. Chellamuthu[2], I. Kanik[1]. [1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109, USA, laura.m.barge@jpl.nasa.gov, [2]University of Southern California, Dept. of Biological Sciences

The alkaline hydrothermal model for the origin of life on wet / rocky worlds (Russell et al. 2013, *Astrobiology* in revision) can be partially modeled as a fuel cell, and we will show how laboratory simulations of the origin of life in general can benefit from this out-of-equilibrium, systems-led approach. We term this the "prebiotic fuel cell" (PFC) operating at a putative Hadean hydrothermal vent or at an icy world seafloor interface, and will present preliminary results utilizing electrochemical analysis techniques and proton exchange membrane (PEM) fuel cell components to test the properties of this and other geo-electrochemical systems. The modular nature of fuel cells makes them ideal for creating geo-electro-chemical reactors to simulate hydrothermal systems on wet rocky planets and characterize the energetic properties of the seafloor / hydrothermal interface. Preliminary experiments simulating hydrothermal chimney growth on electrode materials reveal that self-assembling inorganic precipitate membranes (analogous to components in hydrothermal chimneys) have many unusual properties that may be biologically and/or prebiotically relevant, probably including preferential ion-exchange, charged surfaces that could maintain ion membrane potentials, and/or electrical conductivity. The mineral precipitates formed at the interface of contrasting solutions in our experiments represent specific components that would have been contained within the larger, carbonate- and silica-containing precipitates formed at an alkaline hydrothermal vent on the early Earth (or at a serpentinizing system on Europa or Enceladus). Iron sulfide precipitates, formed in pH / ion gradients via diffusion and self-assembly, could contribute to the electrocatalytic properties of a hydrothermal chimney if they were capable of electron conduction. In some ways, the inorganic Fe/S precipitates formed on carbon cloth/felt in our interface experiments are similar to the ion-exchange membranes and gas diffusion layers in commercial as well as experimental fuel cells. This preliminary success of using commercially available fuel cell electrode/GDL material as a template to precipitate simulated hydrothermal mineral catalysts is quite promising, as these can be directly used in PEM fuel cell assemblies to catalyze redox reactions in a pressurized out-of-equilibrium geology test-bed reactor. Conducting this type of laboratory simulation of the emergence of bioenergetics will not only be informative in the context of the origin of life on Earth, but may help us understand whether it is possible for life to have emerged in similar environments on icy worlds.

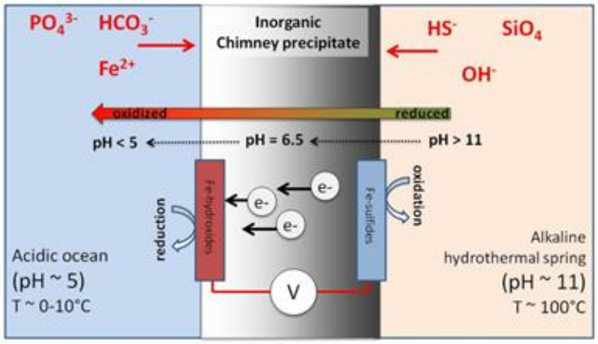


Figure 1: Fuel Cell model for the emergence of metabolism in a serpentinizing system on a rocky / icy world. (Barge et al. in review)

Figure 2: Fuel cell experiments to simulate geochemical seafloor interfaces on Europa or Enceladus.

References: [1] Russell, M. J. et al. (in review) *Astrobiology*. [2] Barge, L. M. et al. (in review) *Astrobiology*.

FLYBY SOUNDING OF EUROPA'S ICY SHELL: RADAR INVESTIGATIONS, ANALOGS, AND INSTRUMENTS FOR THE EUROPA CLIPPER MISSION.

D.D. Blankenship[1], A. Moussessian[2], D.M. Schroeder[1], K.M. Soderlund[1], C. Grima[1], Y. Gim[2], J.J. Plaut[2], B.E. Schmidt[3], [1]Institute for Geophysics, University of Texas at Austin, TX, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [3]Georgia Institute of Technology Earth and Space Sciences, Atlanta, GA

The Europa Clipper is a NASA mission concept to study Europa, the ice-covered moon of Jupiter, though a series of fly-by observations of the Europan surface and subsurface from a spacecraft in Jovian orbit. One of the primary instruments in the strawman scientific payload is a multi-frequency, multi-channel ice penetrating radar (IPR) system. The IPR will play a critical role in achieving the missions science objectives for Europa's ice shell, which are to characterize the distribution of any shallow subsurface water, search for an ice-ocean interface and evaluate a spectrum of ice-ocean exchange hypotheses..

The Europa Clipper mission concept presents a range of technical challenges and opportunities for ice penetrating radar science and engineering. The flyby-centric mission configuration is an opportunity to collect and transmit minimally processed data back to Earth and exploit advanced processing approaches developed for terrestrial airborne data sets. The mission concept also includes using the IPR as a nadir altimeter capable of measuring tides to test ice shell and ocean hypotheses as well as characterizing roughness across the surface statistically to identify potential follow-on landing sites. [1,2] Finally, the observation and characterization of subsurface features beneath Europa's chaotic surface requires discriminating abundant surface clutter from a relatively weak subsurface signal. We will present instrument design and data processing concepts for addressing these challenges.

The development of successful instrumentation and data interpretation techniques for exploring Europa should leverage analogous terrestrial environments and processes. Towards this end, we will discuss a range of terrestrial radio glaciological analogs for hypothesized physical, chemical, and biological processes on Europa and present airborne data collected with the University of Texas dual-frequency radar system over a variety of terrestrial targets. These targets include water filled fractures, brine rich ice, water lenses, accreted marine ice, and ice surfaces with roughness ranging from firn to crevasse fields and will provide context for understanding and optimizing the observable signature of these processes in future radar data collected at Europa [3,4,5].

References:

[1] Pappalardo, R. T., et al. "Science Potential from a Europa Lander." Astrobiology 13.8 (2013): 740-773. [2] C. Grima, D.M. Schroeder, D.D. Blankenship, D.A. Young. Planetary Landing Zone Assessment by Radar Sounder: Demonstration in Antarctica, Planetary and Space Science (in prep), [3] Blankenship, Donald D., et al. "Radar sounding of Europa's subsurface properties and processes: The view from Earth." Europa, edited by RT Pappalardo, WB McKinnon, and KK Khurana (2009): 631-654., [4] Schmidt, B. E., et al. "Active formation of/chaos terrain/'over shallow subsurface water on Europa." Nature (2011). [5] Peters, Matthew E., et al. "The distribution and classification of bottom crevasses from radar sounding of a large tabular iceberg." Geoscience and Remote Sensing Letters, IEEE 4.1 (2007): 142-146.

THE H_2O-MGSO$_4$ SYSTEM AND THE PERSPECTIVE OF DEEP OCEANS FOR LARGE ICY MOONS.

O. Bollengier[1], O. Grasset[1], Erwan Le Menn[1] and G. Tobie[1], Université de Nantes, CNRS, Laboratoire de Planétologie et Géodynamique de Nantes, UMR 6112, 44322 Nantes Cedex 3, France (olivier.bollengier@univ-nantes.fr).

Introduction: Experimental and theoretical evidences support the presence of subsurface oceans under the icy crusts of Ganymede, Callisto, Europa and Titan. The perspective of long-term aqueous reservoirs and geological activity makes these bodies top candidates for the search of extra-terrestrial life in our Solar System. The planet-sized moons Ganymede and Titan present massive hydrospheres thick enough for dense high-pressure ice phases (H_2O ices III, V and VI) to be stable at their base, at the contact with their silicate mantle. On the contrary, the thinner hydrosphere of Europa do not reach the pressures needed to form these high-pressure ice phases, so that this moon may present the unique case of an ocean directly interacting with silicates [1]. This configuration, favoring the introduction of energy and chemical species in the ocean, makes this particular moon more attractive for potential life forms comparatively to the larger icy satellites [2].

Experiments in the H_2O-$MgSO_4$ system revealed that $MgSO_4$ aqueous solutions become denser than ices III, V and VI at their pressures of stability [3, 4]. As $MgSO_4$ is one of the main salts extracted during aqueous leeching of the most primitive chondrites [3], these results challenge a decades-old paradigm and suggest that deep oceans may be present down to the bottom of the hydrospheres of the largest icy moon, directly above their silicate mantle [4]. This calls for a reconsideration of the habitability of the largest icy moons.

Stability and formation of a deep ocean: These results raise the questions of a) the conditions behind the stability of a deep ocean below a high-pressure H_2O ice phase and b) the mechanisms behind the formation of such deep oceans during the cooling of the moons.

The gravitational stability of an ocean below a high-pressure ice phase layer implies that the $MgSO_4$ solubility at the ice-liquid interface is high enough for the density of the liquid to equal or exceed the density of the ice phase. At any pressure, the maximum solubility of $MgSO_4$ in liquid water is the eutectic composition of the H_2O-$MgSO_4$ system. However, despite several reported experiments [3, 5, 6, 7], this parameter remains essentially unknown beyond 0.4 GPa [8]. Data presently available are sufficient to conclude that the eutectic composition of the system is rich enough for a putative H_2O-$MgSO_4$ ocean to be stable below an ice III or V layer. However, the eutectic composition between 0.6 and 1.0 GPa still need to be determined to confirm of infirm the stability of an ocean at the base of the hydrosphere of Ganymede and Titan.

During the cooling of an icy moon, the progressive crystallization of its hydrosphere results in the concentration of the solute species in the ocean. For deep oceans to form in the hydrosphere, part of an initial, diluted subsurface ocean must migrate through high-pressure ice layers at some point in the history of the satellite. At constant salinity, the higher compressibility of the H_2O-$MgSO_4$ aqueous solutions comparatively to H_2O ice phases [4] implies that any fluid beginning a top-down migration in an ice layer will not be stable until the next ice-ice or ice-silicates interface. However, the thermal profile of the hydrosphere compared to the liquidus of the migrating fluids may result in partial crystallization of the fluid (cold profile) or fusion of the surrounding ice phase (hot profile), thus affecting the density of the fluids and the formation of a deep ocean. However, very limited experimental data have been acquired on the liquidus of the H_2O ice phases between 0 and 0.6 GPa, and no experiment has been reported between 0.6 and 1.0 GPa.

New experiments and modelling: To address these two problems, new high-pressure anvil cell experiments are being carried out to constrain the equilibriums of the H_2O ice phases in the H_2O-$MgSO_4$ system over the 0 – 1 GPa et 250 – 300 K pressure and temperature ranges relevant the hydrosphere of Ganymede and Titan. A quantitative Raman spectroscopic approach has been developed to establish a detailed PTx description of the liquidus of the ice phases at compositions up to the eutectic. These data will be used to establish an ion interaction thermodynamic description of the liquidus that in turn will allow the modelling of the evolution of the massive hydrospheres of satellites such as Ganymede and Titan.

Acknowledgements: The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013 Grant Agreement no. 259285).

References: [1] Vance S. and Goodman J. (2009) in *Europa* (Univ. Arizona Press). [2] Lammer H. *et al.* (2009) *Astron. Astrophys. Rev.*, *17*, 181. [3] Hogenboom D. L. *et al.* (1995) *Icarus*, *115*, 258. [4] Vance S. and Brown J. M. (2013) *Geochim. Cosmochim. Acta*, *110*, 176. [5] Grasset. O. *et al.* (2000) *LPS XXXI*, 1386. [6] Dougherty A. J. *et al.* (2007) *LPS XXXVIII*, 2275. [7] Nakamura R. and Ohtani E. (2011) *Icarus*, *211*, 648. [8] Vance S. *et al.* (2013) *LPS XXXIV*, 1872.

Hydrogen in Enceladus' Plume - Native or Artifact? T. G. Brockwell[1], J. D. Walker[1], S. Chocron[1], J. H. Waite[1], R. S. Perryman[1], B. A. Magee[1], [1]Southwest Research Institute, San Antonio, TX 78228.

Compositional analysis by the Cassini CDA of the ice grains originating in the Enceladus plume indicates the presence of salts (e.g. NaCl) and grains (e.g. SiO_2), which strongly suggest a liquid ocean in the interior of Enceladus that is undergoing active hydrothermal activity. Measurements by Cassini INMS of the minor volatiles found in the plume gas (NH_3, N_2, CH_4, CO, and CO_2) provide a more ambiguous picture, partially due to the inability to distinguish CO from N_2 in the mixture, and also because they portray a mixed picture of the oxidation state of the interior ocean. The identification H_2 in the plume provides a distinct indicator of internal hydrothermal activity and its quantification provides a clear indicator of the oxidation state of the interior ocean.

Results from Cassini INMS demonstrate an increase in hydrogen abundance with increasing spacecraft velocity. Based on evidence in the INMS and CDA data the source of the velocity dependent change has been ascribed to the evolution of fresh titanium within the INMS antechamber by ice grain arrival and subsequent reaction of water with the titanium to produce the observed hydrogen[1].

A recent series of lower velocity flybys of Enceladus has given reproducible plume compositions with very similar hydrogen abundances (though substantially less abundant than the high velocity flybys), but the presence of ice grains leaves open the question of whether the hydrogen present in the plume is native, or created by reaction with titanium and if so then in what proportion?

To better understand the effect of the ice grain impacts on the plume composition a series of impact physics computations were performed to calculate the quantity of titanium unearthed by their impact. This quantity has been used as an input into a surface chemistry model for the antechamber. The model considers both physisorption and chemisorption effects within the antechamber to follow the evolution of the surface and gas phase populations of the antechamber.

The model is used to explore the processes occurring in the antechamber to arrive at a description of the observed flyby data and to constrain the possible contribution of native hydrogen in the plume.

[1] Waite, J.H., et al., *Liquid water on Enceladus from observations of ammonia and 40Ar in the plume.* Nature, 2009. **460**(7254): p. 487-490.

SURFACE TEXTURE AS A CLUE TO WHAT LIES BENEATH ICY WORLDS. B. J. Buratti[1], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109 (bonnie.buratti@jpl.nasa.gov)

Introduction: During the past three decades, radiative transfer models have been fit to photometric measurements of the surfaces of icy bodies to understand the physical nature of their surfaces. The main properties modeled include macroscopic roughness, which includes features ranging from mountains and craters to clumps of particles; the porosity of the optically active portion of the regolith; and the size, composition, and shape of surface particles. Combined with quantitative measurements of albedo as well as compositional information garnered from spectroscopic data, photometric modeling can yield important clues on geophysical evolution including collisional history and volcanic processes. Certain attributes of he surface are markers for habitable environments. High albedo may be the most obvious, as bright ice represents an active surface, one that might have formed through active cryovolcanic events from a liquid mantle. Of course, a high albedo is not a unique marker for a habitable environment: for example, seasonal volatile transport is another possibility.

Photometric modeling has been criticized with claims that it doesn't replicate nature and that it doesn't provide unique solutions. The first criticism is mitigated by accumulating measurements for many types of surfaces, where more emphasis is put on ***comparisons*** among model fits. The second concern is addressed by accumulating measurements at many viewing geometries and by combining disk resolved spacecraft measurements with disk integrated data from both ground-based telescopes and spacecraft. The most relevant parameters for seeking habitable environments on icy bodies are surface texture, and the shape, size, and composition of surface particles.

Roughness: Although roughness doesn't yield a unique signature for habitable environments, Titan's low albedo terrain is much smoother than its bright terrain [1], indicating viscous relaxation and possible saturation of this part of the surface by a liquid.

Surface porosity: It is well known that airless bodies exhibit a nonlinear surge in brightness as their surfaces become fully illuminated to an observer at full moon, or "opposition" in the astronomical terminology. The canonical explanation for this effect is that shadows cast by particles comprising the regolith rapidly disappear at this geometry. "Fluffy" surfaces with large amounts of void space exhibit stronger opposition surges. Quantitative models have been fit to icy worlds to provide measurements of the compaction state [2,3,4]. Both Enceladus and Europa possess tenuous surfaces that could indicate fallout from active cryovolcanic processes from a liquid mantle below. (Titan's atmosphere makes defintinitive measurements more difficult.) One complication of fitting models to icy bodies is that they have high albedos, and confounding effects such as coherent backscatter add additional contributions to the opposition surge. Recent measurements from the *Cassini* Visual Infrared Mapping Spectrometer (VIMS) at 3.6 μm show a dramatic change in the nature of the opposition surge from that at visible wavelengths. At this wavelength multiple scattering is insignificant and analysis of the phase curve enables a direct measurement of the surface porosity. Preliminary results for Enceladus yield a porosity of about 95 [5]%, equal to that of unpacked terrestrial snows. Differences in surface texure also allow the determination of likely areas of localized activity.

Particle size and shape: The single scattering phase function describes the directional scattering properties of a planetary surface. Small transparent particles tend to scatter more isotropically, as some photons survive to exit the particle in the forward direction. One of the first clues of the possibility of active cryovulcanism and associated deposits on Europa was its relatively isotropic single particle phase function [2]. Small particles are not a unique signature for a habitable environment. For example, in the Saturnian system small (micron-sized) particles from the E-ring contaminate the icy moons.

Conclusions: The derivation of physical photometric properties provides a unique tool for remotely sensing habitable envrionments on icy worlds. If disk-resolved measurements from spacecraft can be obtained, areas of activity (e.g., inactive geysers and plumes) can be pinpointed.

References: [1] Buratti, B. et al. (2006) *Planet. & Space Sci.* **54**, 1498. [2] Buratti B. (1985) *Icarus* **61**, 208. [3] Domingue, D. et al. (1991) *Icarus* **90**, 30. [4] Verbiscer, A. et al. (2005). . *Icarus* **173**, 66-83. [5] Buratti, B. et al. (2013). DPS meeting #45, #406.04.

Acknowledgments: This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract to the National Aeronautics and Space Administration.

HYDROCARBON TRAPPING IN TITAN SURFACE MATERIALS.

M. L. Cable[1], T. Vu[1], M. Choukroun[1], C. Markus[1], R. Hodyss[1], M. Malaska[1] and P. Beauchamp[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 (Morgan.L.Cable@jpl.nasa.gov, Robert.P.Hodyss@jpl.nasa.gov)

Introduction: Titan is the only body in the Solar System other than Earth with standing liquids on its surface. In this frigid landscape, the liquid phase is comprised of hydrocarbons such as methane and ethane. Modeling of hydrocarbon lake composition suggests that some organic species may be present at or near their saturation levels [1]. Loss of solvent in the lakes via evaporation or other processes could induce precipitation of these dissolved organics. The 'bathtub rings' observed by Cassini around some of the Northern lakes on Titan may be evidence of formation of such evaporites [2], which may play an important role in the surface chemistry of Titan.

The motivation for this work is to understand the composition and morphology of likely evaporites and other deposits on the shorelines of hydrocarbon lakes on Titan. We focus on benzene, a relatively simple organic molecule that has been detected in Titan's atmosphere by Cassini [3-4], and was found to be the most abundant heavy molecule in Titan's thermosphere [4]. Further, benzene was tentatively identified on the surface of Titan by the GC-MS of Huygens [5], a result that is supported by Cassini VIMS measurements [6]. Recent work in our laboratory [7] indicates that benzene has very low solubility in liquid ethane (<20 mg/L); thus, it would be one of the first and most abundant evaporites to form as Titan lake levels drop.

Methods: Ethane was condensed at Titan surface temperature (90 K) under N_2 atmosphere in a custom-built cryostat. Benzene was either added to saturation or frozen separately to produce a greater quantity of crystalline material. An aliquot of the sample was transferred to a Linkam LTS 350 liquid nitrogen-cooled cryostage maintained at 90 K. The sample was then analyzed within the cryostage using a Horiba Jobin Yvon LabRam HR confocal Raman microscope with a Nd:YAG laser (frequency-doubled 532 nm, 50 mW) as the excitation source and a 1800 gr/mm grating, providing a resolution of 0.4 cm^{-1}.

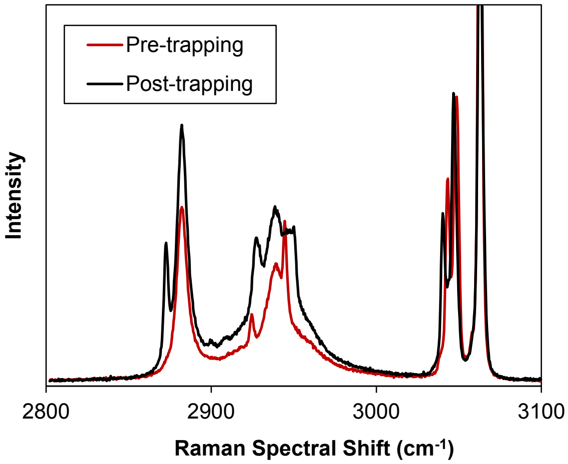


Figure 1. High resolution Raman spectra of crystalline benzene and liquid ethane, pre- and post-trapping.

Results: Precipitation of benzene from liquid ethane produces various crystal morphologies, including hexagonal, needle-like and globular crystals. Trapping of ethane in crystalline benzene was confirmed by Raman spectral shifts of both ethane and benzene peaks (Fig. 1). These spectral shifts, in addition to microscope images (Fig. 2), indicate that benzene and ethane form a new crystal structure upon trapping.

Ethane trapping reaches saturation in minutes at 120 K and in 1.5 hours at 110 K. This suggests that trapping of ethane in a benzene evaporite would occur readily in Titan ambient conditions, implying that evaporite basins may act as important hydrocarbon reservoirs on Titan. Future work will involve investigation of methane trapping in greater detail.

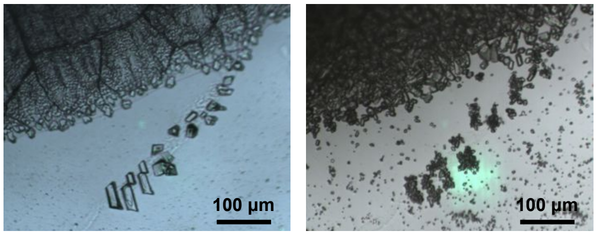


Figure 2. Microscope images (10X) of benzene crystals, pre-trapping (left) and post-trapping (right).

Acknowlegements: This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Support from the NASA Astrobiology Institute (Titan node), the NASA Astrobiology Science and Technology Instrument Development (ASTID) Program, and government sponsorship are gratefully acknowledged.

References: [1] Cordier D. et al. (2009) *Ap J*, *707*, L128. [2] Barnes J. W. et al (2011) *Icarus*, *216*, 136-140. [3] Coustenis A. et al. (2007) *Icarus*, *189*, 35-62. [4] Waite J. H. et al. (2005) *Science*, *308*, 982-986. [5] Niemann H. B. et al. (2005) *Nature*, *438*, 779-784. [6] Clark R. N. et al. (2010) *JGR*, *115*, E10. [7] Malaska M. and Hodyss R. (2013) Personal communication.

A Comparative Analysis of Microbial Diversity in Spacecraft Assembly Facilities and Epsomite Lakes

F. Chen[1], M. La Duc[1], P. Vaishampayan[1], A. Probst[2], M. Schneegurt[3], and B. Clark[4]. [1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, Fei.Chen@jpl.nasa.gov., [2]University of Regensburg, Germany, [3]Wichita State University, and [4]Space Science Institute

Introduction: The icy-moon environment will undoubtedly present a wealth of challenges for microbial survival, and high salt-concentrations might play a significant role in any contaminant microorganism's ability to persist. Initially discovered by the Viking lander, and henceforth confirmed by more recent missions, martian regolith rich in $MgSO_4$. This finding sparks concerns relating to the unlikely event of an off-nominal landing occurring involving a spacecraft equipped with a perennial heat source. Under such conditions, it might be possible for meltwater stemming from the subterranean ice-rich regolith to persist for an extended period of time. Such an environment could serve as refuge for contaminant terrestrial microbes to propagate, sheltered from the countless environmental pressures and stresses above. In lieu of scientific observations that suggest otherwise, such a catastrophic phenomenon should not be omitted from consideration in the context of icy-moon exploration.

$MgSO_4$-tolerant microbes were screened from two distinct environments: spacecraft assembly facilities (SAF) and $MgSO_4$ rich epsomite lakes. The microbial population observed in the former environment suggests the types of microbes most likely to gain access to, and contaminate outbound spacecraft, while microbes populating the latter environment represent phylotypes whose fitness renders capable of surviving $MgSO_4$ rich conditions.

Our results have shown that tolerance to high magnesium sulfate (2 M or more) is not uncommon among halotolerant microbes, common soil microbes, and within the culture collections from JPL SAF clean rooms. Rare epsomite lakes on earth harbor diverse microbial communities apparently dominated by bacteria. Culture collections were obtained from Hot Lake (Oroville, WA) and Basque Lake (Kamloops, BC), and characterized phenetically and genetically. Briefly, isolates from epsomite lakes are mixtures of organisms associated with common soils and hypersaline environments. The isolates are halotolerant and epsotolerant, not requiring high salinities. Many of the isolates can grow at low temperatures (4 °C) and some can grow under anaerobic conditions.

Cultivation-independent molecular techniques were also used to facilitate highly sensitive studies of microbial community structure and dynamics. Next generation DNA sequencing [*i.e.*, 454 tag-encoded FLX amplicon pyrosequencing (TEFAP)] was carried out on environmental samples collected from a spacecraft assembly cleanroom facility, Hot lake, and Basque lake using primers targeting specific hypervariable regions in the bacterial and archaeal 16S rRNA gene. In addition, TEFAP protocols were designed and executed to assay the presence of certain functional genes, such as *nifA* in *Bacillus* spp., *mcrA* in methanogens, and *dsr* in sulfate –reducing microorganisms. Genera belonging to the Rhodobacteraceae family dominated the populations observed from both of the lake samples. *Acidiphilium* spp. was observed in the samples obtained from the JPL-SAF and both of the epsomite lakes. Basque lake samples were dominated by *Methanohalophilus* spp. and other unclassified archaea. The comparative analysis reported here highlights certain characteristics shared between microbial populations originating from two distinct environments relevant to extraterrestrial exploration. The results of this investigation enable more knowledgeable hypotheses pertaining to the types of microbes most likely to (A) gain access to SAF environments and thus pose a larger threat of forward contamination, and (B) persist for extended periods of time once confronted with environmental challenges mimicking epsomite lakes.

References:

[1] J. D. Crisler, T. M. Newville, F. Chen, B. C. Clark and M. A. Schneegurt. (2012) Bacterial growth at the high concentrations of magnesium sulfate found in Martian soils. Astrobiology 12:98-106.

[2] Kilmer, B. R., T. Eberl, B. Cunderla, K. Rowe, F. Chen, B. C. Clark, and M. A. Schneegurt. (2013) Characterization of the microbial assemblage from the saturating magnesium sulfate environment of Hot Lake, WA. International Journal of Astrobiology, in press. doi 10.1017/S1473550413000268.

EFFECT OF AMMONIA ON THE STABILITY OF CLATHRATE HYDRATES: EXPERIMENTAL STUDY.

M. Choukroun[1], T. Vu[1], E. Gloesener[1], A. Ibourichene[2], W. Smythe[1], M. Barmatz[1], R. Hodyss[1]. [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., MS 79-24. [2] Ecole Normale Superieure Paris. (E-mail: Mathieu.choukroun@jpl.nasa.gov).

Introduction: The likely presence of clathrate hydrates on Titan has long been inferred from cosmochemical, thermal, and thermodynamic models (e.g. [1,2]. As gas-laden icy structures (up to 15 % molar), they may be internal reservoirs of methane and other atmospheric gasses, and their dissociation during cryovolcanic activity or their involvement in substitution processes could be main contributors to the replenishment of Titan's atmospheric methane [3,4]. However, the controversial nature of the few cryovolcanic features tentatively detected on Titan by the Cassini spacecraft questions our current understanding of the modalities of outgassing processes.

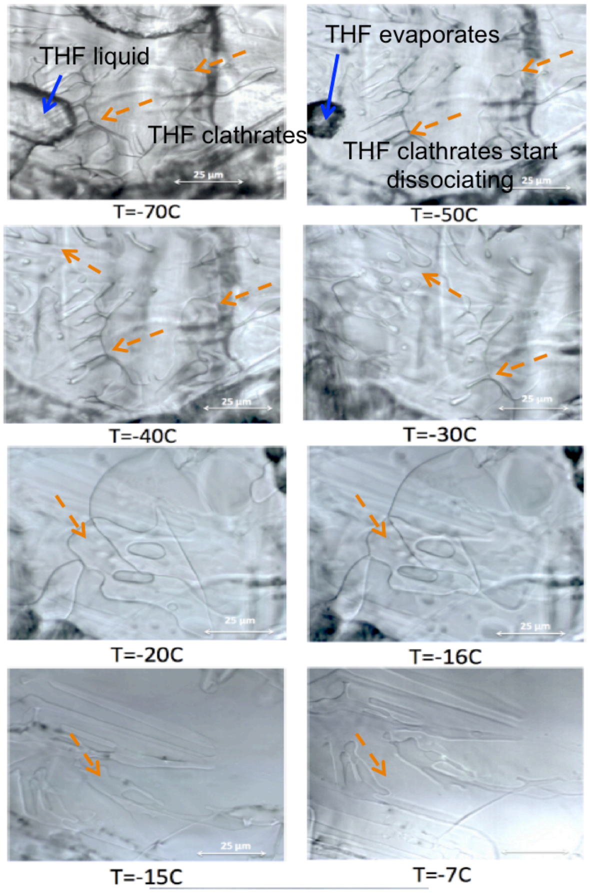
Specifically, the paucity of experimental data on the stability of clathrate hydrates in the presence of ammonia (likely source of Titan's atmospheric nitrogen) and the lack of a fundamental understanding of how such inhibitors affect the phase behavior of clathrate hydrates is a severe limitation for our ability to approach the modalities of outgassing on Titan.

Methods: We are conducting an experimental study in the ternary systems H_2O-CH_4-NH_3 and H_2O-THF-NH_3. Phase diagrams of the former are constructed under pressures up to 100 bars using a high-pressure cryogenic calorimeter, while the latter is investigated at atmospheric pressure using a liquid nitrogen cooled cryostage coupled to a microscope and a Raman spectrometer.

High-pressure calorimeter: This high-pressure cryogenic calorimeter consists of a Setaram BT215 Calvet calorimeter, equipped with 100 bar cells, cooled by liquid nitrogen. A custom gas handling system has been developed, and preliminary measurements obtained on pure gases and on clathrates in the H_2O-CH_4 system [6] validate this method.

1-bar optical cryostage with Raman: This consists of a Linkam LTS 350 cryostage, cooled by liquid nitrogen, that is coupled to a Horiba Jobin-Yvon LabRam HR, equipped with a 532 nm solid-state and a 633 He-Ne lasers, and two gratings, to achieve a spectral resolution of 0.4 cm^{-1} (high resolution grating) to 1 cm^{-1} (low resolution broadband grating).

Results: The main preliminary results are: 1/ although ammonia does affect the stability of clathrate hydrates, its influence appears lower than on the melting of water ice; 2/ the dissociation proceeds incongruently, similarly to the incongruent melting of water ice in the H_2O-NH_3 system. Figure 1 shows microscopic images of THF clathrate hydrates in a 10 wt% NH_3-H_2O solution, which clearly indicate this incongruent melting / partial dissociation process. These results and their implications will be presented at the meeting.



T=-70C T=-50C

T=-40C T=-30C

T=-20C T=-16C

T=-15C T=-7C

Figure 1. Microscope images of the partial dissociation process observed on THF clathrate hydrates in presence of 10 wt% ammonia in aqueous solution.

Acknowledgements: This work has been conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Support by the NASA Outer Planets Research Program and government sponsorship acknowledged.

References: [1] Lunine J.I. and Stevenson D.J. (1987) *Icarus* 61, 70-77. [2] Tobie G. et al. (2006), *Nature* 440, 61-64. [3] Lunine J.I. et al. (2009) In: Titan from Cassini-Huygens, U. Arizona Press, 35-59. Choukroun M. and Sotin C. (2012) *Geophys. Res. Lett.* 39, L04201 [4] Choukroun M. et al. (2010) *Icarus, 205,* 581-593. [5] Sloan E. D. (1998), *Ed: Marcel Dekker, N.Y.*

The Geophysical “No-Man's Land” of Transport across Ice Shells.

Geoffrey C. Collins[1], Amy C. Barr[2], and Rosaly M. Lopes[2], [1]Wheaton College, Norton MA 02766 gcollins@wheatoncollege.edu, [2]Brown University, Providence RI, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA.

Introduction: Icy world habitability may depend on the mechanisms and rates of processes controlling vertical transport of materials through floating ice shells on top of liquid water oceans. While these processes can supply nutrients and oxidants across the ice shell, they can also be a conduit for harmful contamination of the ocean from unsterilized spacecraft at the surface. Thus this topic is critical from both an astrobiology and a planetary protection standpoint.

When thinking about a cross-section through an ice shell, some vertical teanspport processes operate from the top down, and some from the bottom up (Fig. 1). Top-down processes often operate to a maximum depth in the shell, while bottom-up processes are limited to a maximum height. If there is vertical overlap between top-down and bottom-up processes, then material can be transported through the ice shell. If there is no overlap, a geophysical “no-man’s land” exists in the middle of the ice shell, blocking vertical transport. We explored this topic in some detail in a recent NRC report on planetary protection of icy bodies [1], and present it again here to spark discussion on its relationship to the habitability of icy worlds.

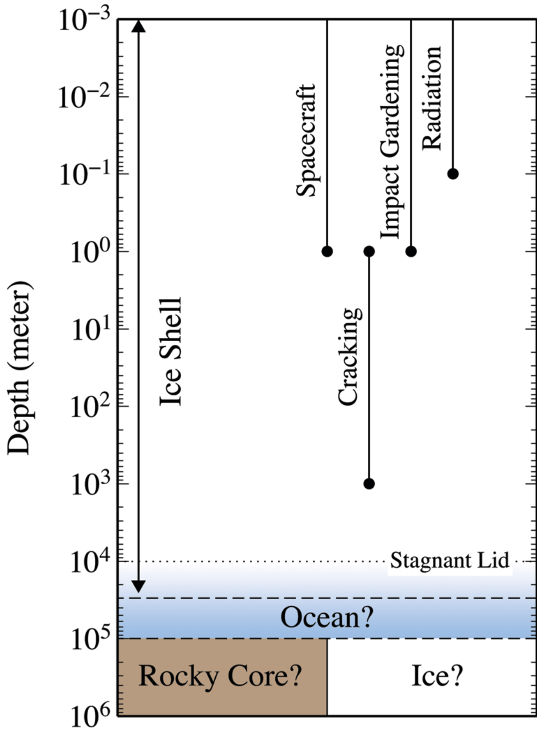


Figure 1: Schematic diagram of vertical transport processes on a generic icy world with an ice shell of order 10 to 100 km thick [from ref. 1]. In this schematic, top-down transport processes do not overlap with the bottom-up process of convection, creating a “no-man’s land” blocking vertical transport of materials.

Processes: At the surface of an icy world are regolith processes. Radiation may affect materials within centimeters of the surface. The rain of small impactors on airless worlds churns the surface regolith within top meters of the regolith; on Europa this rate of impact gardening may be 1 meter depth of vertical mixing over 10 million years [2].

Below the surface regolith, the underlying ice may produce open tensile fractures, providing another potential top-down pathway into the ice shell. The depth of propagation of open tensile fractures is limited by surface gravity, limiting the depth of transport by open surface cracks to hundreds of meters on a large icy world comparable to the Galilean satellites, and kilometers on an icy world comparable to the mid-size satellites of Saturn.

Cryovolcanism is a bottom-up process limited by the negative buoyancy of water relative to ice, though several mechanisms have been proposed that could enhance transport of liquid from the bottom to the top of an ice shell. Whether surface liquid can then drain back to the interior is a different question. Such large-scale drain-back is rare in terrestrial volcanism, and is associated with lava lakes or eruptions of low viscosity basaltic lava. Producing and keeping melt stable near the surface of an icy world is challenging from an energy standpoint.

Convection is another important vertical transport process, and convective flow velocities could transport material from the top of the convecting layer to the base of the ice shell in 10^5 years [3]. On top of the convecting layer of most icy worlds is a stagnant lid kilometers thick that does not participate in convective motions. For most worlds, this stagnant lid presents a barrier to vertical transport, but on Europa and Enceladus, localized high heat flows may lead to plastic yielding and mobile lid behavior [e.g. 4] that could promote transport of material to the subsurface.

References: [1] Sogin et al., Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies, *National Academies Press*, 2012. [2] Phillips and Chyba, *LPS XXXII*, #2111, 2001. [3] Barr et al., *JGR*, 2004. [4] Showman and Han, *Icarus*, 2005.

Icy World Transport Processes and Planetary Protection

Catharine Conley

Small-scale particle transport processes in mixed solid-liquid systems are complex, and the consequences can be far-reaching. Even on Earth, the details of subsurface transport processes are not well understood -- despite this, microbes can be collected from multiple kilometers down into the crust, so effective transport mechanisms must exist. Understanding micron-scale and larger subsurface transport processes in liquid-solid mixtures is important for assessing the risk, due to exploration, of contamination that could interfere with future scientific study. Planetary protection considerations for icy bodies in the outer solar system involve maintaining a sufficiently low probability of introducing a viable Earth organism into a liquid water (or warm ice) environment. Developing a better understanding of the detailed mechanisms of subsurface particulate transport, by which microbes carried on spacecraft could be transported to possible habitats within icy objects, could lead to improvements in planetary protection practice.

JOVIAN MAGNETOSPHERIC IMPACTS ON DETERMINATION OF EUROPA'S ASTROBIOLOGICAL POTENTIAL.

J. F. Cooper[1] and E. C. Sittler[2], [1]Heliospheric Physics Laboratory, Code 672, NASA Goddard Space Flight Center, Greenbelt, Maryland (John.F.Cooper@nasa.gov); [2]Geospace Physics Laboratory, Code 673, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771 (Edward.C.Sittler@nasa.gov).

Introduction: The astrobiological potential of Europa, as a potential abode for past or extant life, is linked to the three major resources considered necessary for life as we know it: liquid water, organic chemistry, and energy. It is highly probable from magnetic field and geologic evidence, if not yet yet definitely established, that a global water ocean exists below the surface. The basic elements for potential evolution of organic life have likely been present within Europa since its accretional formation, and continue to be delivered by cometary impacts. External irradiation by iogenic and other jovian magnetospheric ions delivers additional elemental materials to the moon surface. Finally, the energy of irradiation by energetic particles oxidizes surface water ice, drives sulfate chemistry, and may also destroy organic signatures of emergent oceanic life at the exposed surface. Jovian magnetospheric interactions potentially contribute to the evolution of life, e.g. through oxidant production, and to detection of the ocean abode through induced magnetic fields. A "habitability" research program for Europa should address the availability of all these resources.

Magnetic Fields: Europa's magnetic field environment arises mainly from interaction of the local magnetospheric field with conducting materials below the surface in the putative salty ocean and with the moon ionosphere arising from UV and magnetospheric particle sputtering of the icy surface. Major periodicities arise from the 11-hour synodic rotation period of the tilted planetary magnetic field and the 85-hour orbital motion of Europa around Jupiter. Any measurement of the oceanic component of the induced magnetic field from these periodic effects must also contend with removal of the ionospheric background fields as Europa moves through the magnetospheric plasma sheet. The varying orientation of the magnetospheric field at the moon surface also impacts the hemispheric and local topographic distributions of irradiation.

Chemistry: The topographically varying surface consists mainly of water ice detectably overlain to various degrees by sulfur hydrates and some trapped gases, O2 and CO2. Since other oxidants including hydrogen peroxide are expected to form in the irradiated ice, the detectable lifetime of recognizable organic compounds, e.g. either emergent from the ocean or delivered by cometary impacts, should be short. There is a very apparent hemispheric asymmetry in the sulfate distributions which correlate strongly to the expected patterns of electron and iogenic sulfur ion irradiation. Low-energy high-flux electrons can only irradiate the trailing hemisphere, while higher-energy (>20 MeV) low-flux electrons bombard the leading hemisphere. The detected sulfates concentrate in the more heavily irradiated trailing hemisphere. Possibly the patches of CO2 arise from oxidation of oceanic or meteoritic organics as the primary sources of carbon. Carbon is unlikely to survive in reduced organic form on the highly oxidized surface, although there might be refugia of fresh organic material in locations shielded by local topography. The most enduring chemical signatures of oceanic life emergent to the surface might be concentrations of calcium, carbon, etc from irradiated remnants of biominerals. The bones and shells of marine life would detectably survive far longer than the organic biosignatures.

Energy: As on Earth we expect that a confluence of energy sources must be available to create habitable conditions, e.g. heating of ice to form liquid water, and to drive biochemistry. The requisite gradient in oxidation potential is provided by the external irradiation of the surface ice to form oxidants and by the primordial formation of the interior ices from reduced materials. Heat energy is mainly provided by tidal dissipation but also to lesser degree in modern times by radioisotope decay. Neither solar UV nor particle energy is deliverd evenly to the global hemispheric or local topographic surface, so surface variations in energy flux are expected. If surface oxidants are to be delivered to the subsurface ocean environment, this occurs by some combination of ice convection, chemical leeching of surface ices by emergent oceanic fluids, and brine channeling. Any active cryovolcanic plumes could be signs of chemical heating from the ocean source or of comet-like release of stored chemical energy in the upper ice crust. A living world is likely visibly active.

Conclusions: There is a long history of mission designs since the eight Galileo mission flybys to determine habitability of Europa. The planned Clipper multiple-flyby mission will contribute greatly to knowledge of surface ice structure, topography, and chemistry, but only an orbiter could definitely track the periodic forcing of the induced magnetic field and ionospheric environments by the 11-hour and/or 85-hour responses of Europa to the external magnetospheric and gravitational environment. A combination of orbital and flyby missions would be optimal.

Heat Transfer from a Shallow Water Sill on Europa – Habitable Zone?

Kate Craft,[1] Wes Patterson[1] and Robert Lowell[2], [1]The Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, Kate.Craft@jhuapl.edu, Wes.Patterson@jhuapl.edu, [2]Virginia Tech, Blacksburg, VA 24061, rlowell@vt.edu

Introduction: Recent work has suggested that lithospheric flexure and flanking fractures observed along some ridges on Europa are best explained by the initial presence of a shallow (~ 1- 2 km deep) liquid water sill [1]. Once a sill forms, a sill lifetime of ~ 100 kyrs of years is required to allow formation of the multiple generations of ridges observed [1]. Previously, we suggested such a water sill could form through a sequence of events involving: fracturing from within the ice shell down to the ocean, pressure driven water flow through the fracture to the shallow subsurface and horizontal fracturing [2],[3]. However, sill lifetime remains a problem. Here we further investigate the sill system and its temperature evolution over time in an effort to characterize the challenges such a long lifetime presents. We also explore these regions as habitable environments.

Sill solidification and heat transfer: Following the typical Rayleigh number calculation, $Ra \approx \rho g \alpha \Delta T D^3/\mu\kappa$ for a fluid body, a 10 to 100 m thick sill has a high Ra ~ 10^{11} for ΔT=1°C. The sill will therefore convect and time for solidification is calculated as: $\tau_S \approx \frac{\rho_W L D^2}{Ra^{1/3} k \Delta T}$, resulting in a sill lifetime of 10s of hrs to a few days. As the sill cools, heat transfers to the overlying ice and the evolving temperature regime can be approximated by assuming that the heat content of all space must equal the original heat content, Q, of the sill at any time, t:

$$T = \frac{Q}{2\rho c\sqrt{\pi\kappa t}} e^{-y^2/4\kappa t} + T_0$$

following [4]. Figure 2 shows the temperature evolution over time for a 1-km deep, 100-m thick sill.

Sill lifetimes, τ_s, are orders of magnitude less than the timeframe suggested necessary by [1]. Temperature gradients shown in Figure 1 depict how a significant rise in temperature only occurs a short distance from the sill center. These findings present a challenge to enabling flexure for ridge formation. Further calculations to determine the minimum temperature needed to enable ridge flexure will be performed to provide more exact quantification of the sill dimensions and lifetime needed. To increase sill lifetime, consideration of brine formation and water replenishment will be investigated.

Habitability region: The temperature profile in Figure 1 can be used to suggest a region outside the sill that could be conducive to life based on the presence of water and the temperature. Previous work by [5], based on organism communities observed near ocean ridges, show a habitable zone in a fluid filled permeable region near an ocean ridge in the temperature regime from 120°C and below [6]. Low temperature communities also exist on Earth that may prove valuable analogs. If a shallow sill formed on Europa, it could possibly transport organisms and enable them to persist (at least for a short period) within the upper few kilometers of the surface.

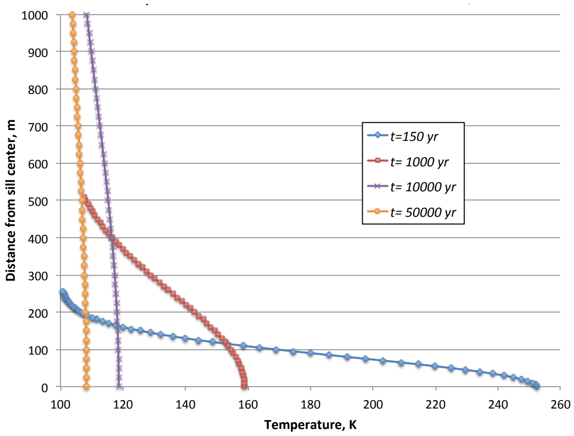


Figure 1. Temperature from center of 100 m thick sill at times, *t*

Summary: Shallow water sills on Europa can enable the flexuring of icy shell as observed at some double ridges as modeled by [1]. These warm water regions could provide habitability zones that warrant further investigation. Lifetimes of 10-100 m thick sills are short, however, and present challenges when comparing to the expected time of formation for double ridges. Further analyses into these issues are ongoing.

References: [1] Dombard et al. (2013) *Icarus, 223,* 74-81. [2] Craft et al. (in prep) [3] Craft, K. L., G. W. Patterson, R. P. Lowell (2013) *LPSC XXXXIV*, #3033. [4] Turcotte, D. L. and G.S. Schubert (2002) Geodynamics, *Cambridge*, 2nd ed. 496pp. [5] Craft, K. L. and R. P. Lowell (2008) *AGU* [6] Johnson et al. (2006),*Geofluids, 6*, 251–271

DOUBLE RIDGES ON EUROPA ACCOMMODATE SOME OF THE MISSING SURFACE CONTRACTION.

C. Culha[1], A. Hayes[2], M. Manga[1], A. Thomas[3], [1]University of California, Berkeley, Department of Earth and Planetary Science, (307 McCone Hall, Berkeley, CA 94720-4767, c.culha4@berkeley.edu), [2] Cornell University, Center for Radiophysics and Space, [3]Stanford University.

Introduction: The two most abundant types of lineaments on Jupiter's moon, Europa, are bands and double ridges. Bands have long been recognized as sites where new crust is formed [1-4], but there are no obvious features that record contraction sufficient to balance the surface expansion produced by bands[5-8]. Here we use geometric analysis to show that some double-ridges accommodate net contraction.

There are various proposed models to explain how bands and double-ridges form. These include: diapirism[9], spreading to make bands[10], folding to make both bands and ridges[11], shearing to make ridges[12], opening-mode fractures[13], and shearing of opening mode fractures[14]. Each of these models predicts different lineament-normal displacements, permitting an observational test that can discriminate among many of these models.

Methods: Here we use Galileo Solid-State Imaging (SSI) images to map the displacements along lineaments. We exploit cross-cutting relationships to map and calculate both strike-slip and normal displacements. We illustrate this procedure in Figure 1 where we consider the case of a ridge which records expansion and right-lateral strike-slip along its centerline.

Results: Double ridges can have either right or left lateral strike-slip displacement. Of the 16 mapped double ridges, 8 show contraction (between 0.04±0.29 and 1.40±0.11 km); 8 show expansion (between 0.05±0.29 and 1.09±0.18km). Bands record right and left lateral motion and involve a component of expansion (between 0.94±0.35 and 8.61±0.85 km). Our results confirm previous studies that show that typical bands are formed by expansion and strike-slip motion[9, 10, 14].

Discussion: One puzzling aspect of the tectonic features on the surface of Europa is the paucity of features that record contraction to balance the expansion produced by bands**.** We find that some double ridges preserve contraction in their cross-cutting relationships. The ridges are spaced on 7.2±3.5 km apart. The average fault-perpendicular displacement for all 16 double ridges (including the ones with expansion) is 0.16±0.06 km (net contraction). The implied mean strain is ~2.2±0.8%. The mean spacing for bands is 43.8±15.7 km. The average fault-perpendicular displacement for 6 bands is 3.3±0.3 km. If generalized, our results imply a mean strain of ~7.6±3.7%, which is consistent with the pole-to-pole mapping done in Figueredo and Greeley[15].

By analyzing cross-cutting relationships along lineaments, we are able to identify displacements both along strike and perpendicular to the lineament. We quantitatively confirm that double ridges can record contraction[16]. We also confirm that bands show expansion, but the recorded expansion along strike is less than the morphologic width. Up-scaling to a global estimate of contraction across ridges, we suggest that the expansion recorded by bands may be partly accommodated by contraction about ridges. These measurements provide constraints for the models that explain the formation of bands and double ridges.

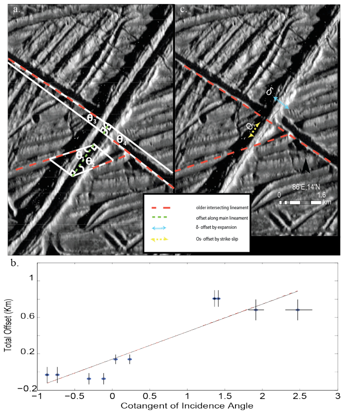


Figure 1: a) An example of a cross-cutting feature on Europa. The incidence angle (θ) is the angle between the main lineament and the older lineament. Each of the offset displacements, marked by the dashed green line in a, is compared to the incidence angle. b) The y-intercept gives the total offset by strike slip (O_S) and the slope is the expansion (δ). c) Reconstructed ridge after removing the strike-slip motion and expansion based on the fit in b).

References: [1] Schenk, P.M. & McKinnon, W.B. (1989) *Icarus,* **79,** 75-100. [2] Pappalardo, R. T. & Sullivan, R.J. (1996) *Icarus,* **123,** 557-567. [3] Sullivan, R.J., et al., (1998) *Nature,* **391,** 371-373. [4] Tufts, B.R., Greenberg, R., Hoppa, G. &Geissler, P. (2000) *Icarus,* **146,** 75-97. [5] Sarid, A.R., Greenberg, R., Hoppa, G.V., Hurford, T. A., Tufts, B.R., & Geissler, P. (2002) *Icarus*, **158,** 24-41. [6] Pappalardo, R.T. & Davies, D.M. (2004) LPI Contribution No. 1357, Lunar and Planetary Institute, Houston. [7] Greenberg, R. (2004) *Icarus*, **167(2),** 313-319. [8] Patterson, G. W. & Pappalardo, R.T. (2002) LPI Contribution No. 1357, Lunar and Planetary Institute, Houston. [9] Head, J. W., & Pappalardo, R. T. (1999) *J. Geophys. Res.*, **104,** 27143-27155. [10] Prockter, L.M., et al. (2002) *J. Geophys. Res.,* **107,** 4/1-28. [11] Manga, M. & Sinton, A. (2004) *J. Geophys. Res.,* **109,** E09001. [12] Nimmo, F. & Gaidos, E. (2002) *J. Geophys. Res.,* **107,** 5/1-9. [13] Greenberg, R. et al. (1998) *Icarus,* **135,** 64-78. [14] Aydin, A. (2006) *J. of Struct. Geol.,* **28,** 2222-2236. [15] Figueredo, P.H. & Greeley, R. (2004) *Icarus*, **167,** 287. [16] Patterson, G. W., Head, J. W. & Pappalardo R. T. (2006)*J. Struct. Geol.,* **28(12),** 2237-2258.

THE EFFECT OF RAYLEIGH-TAYLOR INSTABILITIES ON THE THICKNESS OF UNDIFFERENTIATED CRUST ON KUIPER BELT OBJECTS.

S. J. Desch,[1] M. E. Rubin[1] and M. Neveu,[1], [1]School of Earth and Space Exploration, Arizona State University (steve.desch@asu.edu).

Introduction: The existence of subsurface water on Kuiper Belt Objects (KBOs) is a recently recognized possibility. Calculations by [1] suggest that the present-day Kuiper belt may contain liquid water comparable in total mass to the Earth's ocean. This liquid would be in contact with a relatively warm rocky core, enabling chemical reactions like serpentinization that may be favorable for habitability. The existence of subsurface water is greatly aided by the presence of a thick (50-100 km) layer of ice and thermally insulating rock, that remains cold enough during the KBO's evolution to remain undifferentiated.

The calculations by [1] of the internal structure and thermal evolution of Kuiper belt objects (KBOs) uniquely predict that KBOs should only partially differentiate, with rock and ice separating into a rocky core and icy mantle, below an undifferentiated crust of ice and rock. An objection to these models is that a dense rock/ice layer resting on an icy mantle is gravitationally unstable and prone to Rayleigh-Taylor (RT) instabilities, and may potentially overturn. Here we calculate the ability of RT instabilities to act in KBOs, and determine the thickness of undifferentiated crusts.

Calculation: To calculate the growth rate of RT instabilities, we use the formulation of [2], who calculated the growth rates in the case that viscosity in the dense layer varies exponentially with temperature, which varies linearly with depth. We use the treatment of [3] to calculate the ice viscosity, including such non-Newtonian creep mechanisms as dislocation creep, grain-boundary sliding and basal slip, as well as diffusion creep. We find that for Charon-like bodies (mean density 1.65 g cm^{-3}, radius 605 km), crustal overturn within the age of the solar system is only possible for ice viscosities corresponding to temperatures much higher than typical KBO surface temperatures of 40 to 60 K. Given the fact that thermal evolution models [1] predict that shells within KBOs remain at their maximum temperatures for about 1.5 Gyr, a minimum temperature of 150 K is needed for RT instabilities to overturn layers. Due to the effectively exponential dependence of viscosity on temperature, a similar cutoff temperature arises for KBOs across the range of plausible parameters.

We couple this result to thermal evolution models of KBOs [1] to calculate the thickness of undifferentiated crust on KBOs. We find that on Charon-like bodies the RT instabilities cannot act on geological timescales within about 60 km of the surface. This is less than the 85 km previously calculated for Charon by [1], but is still significant, representing ≈ 25% of the mass of the KBO. While RT instabilities can overturn some of the dense ice/rock layer with the underlying pure ice mantle, their effects are ultimately limited by the low temperatures and high ice viscosities of KBOs.

These calculations referred to Charon specifically, but they are more universal than this. There is little sensitivity of the critical temperature for differentiation to the specific parameters describing a KBO; it is usually around 150 K. Temperatures about 100 K higher than the typical surface temperature are needed to soften the ice enough for layers to overturn. Given typical temperature gradients in bodies around Charon's size, 0.5 K/hm, it is likely that all KBOs that accrete as cold homogeneous ice/rock mixtures will retain undifferentiated crusts. We explore these and other issues in [4].

Unfortunately, refined calculations presented in [4] also indicate that the slight decrease in crustal thickness from 85 to 60 km, does affect the length of time a subsurface ocean can exist. Including only the effects of ammonia as an antifreeze, [4] calculate that Charon would retain subsurface liquid for 3.5 Gyr (compared to the 4.5 Gyr calculated by [1]). Inclusion of methanol as an antifreeze may prolong the lifetime of the ocean 0.5 – 1 Gyr.

Regardless of the details, the conclusion stands that thick, undifferentiated crusts of ice and thermally insulating rock will exist around KBOs, and they will aid in the retention of subsurface liquid. A significant amount of liquid water may exist in KBOs, enhancing the habitability of these bodies.

References:

[1] Desch, S. J., Cook, J. C., Doggett, T. C. & Porter, S. B. (2009) *Icarus* 202, 694-714. [2] Molnar, P., Houseman, G. A. and Conrad, C. P. (1998) *GJI* 133, 568-584. [3] Goldsby, D. L. and Kohlstedt, D. L. (2001), *JGR* 106, 11017. [4] Rubin, M. E., Desch, S. J. and Neveu, M. N. (2014), submitted to *Icarus*.

How Quickly does Drifting Material Traverse Europa's Ocean?

R. Farber[1], J. C. Goodman[2] [1]Wheaton College, Norton MA 02766, farber_ryan@wheatoncollege.edu [2]Wheaton College, Norton MA 02766, goodman_jason@wheatoncollege.edu

Introduction: Europa's putative under-ice water ocean is likely to be driven by geothermal heating from the sea floor, creating buoyant hydrothermal plumes. These plumes may allow for the transport of material (including salts, nutrients and hypothetical organisms) from hydrothermal vents on the ocean floor to the ice shell above. We performed simulations of vertical transport processes in these plumes using the MIT GCM ocean circulation model in an effort to estimate transport times of material through the depth of Europa's ocean. This timescale is significant for astrobiologists interested in hypothetical metabolic cycling of nutrients [1], and also to discussions of planetary protection [2].

Methods: We suppose Europa's ocean is unstratified and deep (≈ 100 km), and assume the plume's buoyancy is controlled by temperature rather than composition. In addition to monitoring the progress of the plume as in [3], we inserted neutrally buoyant Lagrangian tracer particles into the model to trace the movement of drifting material (Figure 1). We analyzed the statistical properties of tracer motion within this model, and used it to extrapolate the typical time required for tracers to traverse the ocean.

We modeled the turbulent transport as a 1-dimensional random walk process. The walk step times and distances were chosen by measuring the decorrelation time for the floats' velocity in the MIT GCM simulation — the walk time step should be equal to the time required for tracer velocity in the model to become randomized, and the walk step distance is equal to the typical height change for the tracer in that time. For a simple symmetric random walk, the position variance is just equal to the number of walk steps [4]. We can thus obtain a statistical estimate of the time required for a majority of tracers to travel a distance equal to the ocean thickness.

Results: When turbulence is provided by a 1-GW hydrothermal plume near Europa's pole, the median time for tracers to disperse through a 100-km-deep ocean is about 1000 years. The rate of tracer dispersion is constant over most of the water column, but is ten times slower than average near the ice/water interface at the top of the model ocean: turbulent mixing is probably weaker there due to the fluid mechanical "law of the wall" [5]. Random transport by turbulence is much faster than transport via the time-averaged flow: turbulent mixing is the dominant factor in transporting astrobiological material in Europa's ocean.

In ongoing work, we are investigating how this transport time depends on plume thermal power and on planetary latitude, and are using Monte Carlo simulations to address the inhomogeneous tracer dispersion rate. Our approach is highly general, and can be adapted to any turbulent simulation of a planetary ocean.

References: [1] Hand K. P. and Carlson C. P. and Chyba C. F. (2007) *Astrobiology, 7,* doi: 10.1089/ast.2007.0156. [2] Sogin M. L. *et al* (2012) *Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies,* National Academies Press. [3] Goodman, J. C. and E. Lenferink (2012) *Icarus* 221, doi: 10.1016/j.icarus.2012.08.027 . [4] Gould, H. and Tobochnik, J., *Statistical and Thermal Physics*, Princeton University Press. [5] von Karman, Th. (1931) "Mechanical Similitude and Turbulence", *Tech. Mem. NACA*, no. 611.

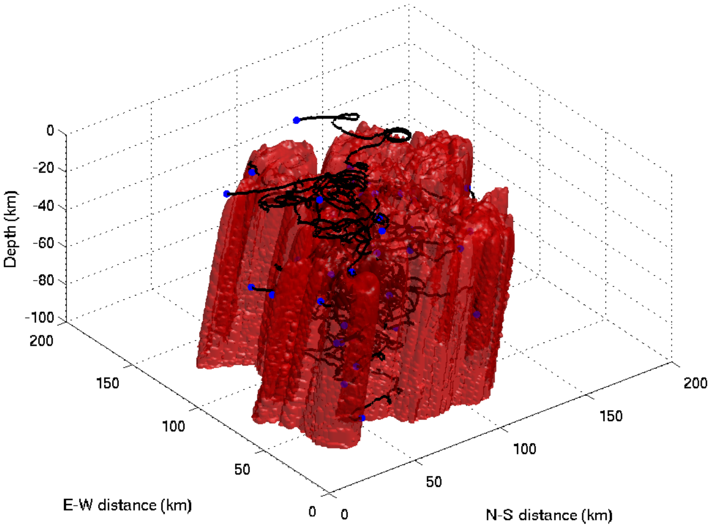


Figure 1: Tracer transport in a simulated hydrothermal plume. Simulation parameters: Seafloor heat flux = 1 GW; ocean depth = 100 km; planetary rotation = 80° latitude on Europa. This snapshot taken 1.7 Earth years into the model run. Red: Ocean temperature isosurface (T > 10^{-9} K above ambient). Blue dots: current position of a subset of tracer particles. Black lines: past trajectory of tracers.

BIOLUMINESCENCE: A POTENTIALLY CONVERGENT SIGNATURE OF LIFE IN FUTURE EXPLORATION OF EUROPA'S SUBSURFACE OCEAN.

C. L. Flores Martinez[1], [1]University of Heidelberg, Centre for Organismal Studies, Im Neuenheimer Feld 234, 69120 Heidelberg, Baden-Wurttemberg, Germany, e-mail: c.flores@stud.uni-heidelberg.de

Introduction: The long-term exploration strategy of Europa and its potential global subsurface ocean envisions the future *in situ* probing for life of the local aquatic environment with an integrated approach that uses a melting probe carrying a second-stage autonomous underwater vehicle (AUV). However, accurately predicting the exact nature of putative biological activity on Europa is extremely difficult. This is due to an unsolved and fundamental problem in evolutionary biology, namely the contingency vs. convergence debate. It is far from certain if stable trajectories exist, leading from mechanistically identical origins of life towards higher forms of biological organization, which are independently and repeatedly, and thus in a convergent manner, traced by the process of evolution within planetary biospheres apart from Earth. Therefore it appears to be useful to address the possibility of convergent evolution in two unrelated evolutionary systems that emerged and subsequently evolved and developed independently. [1,2]

Convergent Evolution and Biosignatures: Firstly, basic theoretical considerations are undertaken pertaining to the possibility of convergent biological processes occurring at an interplanetary and cosmic scale in a Universe that seems to exhibit a natural propensity towards biogenesis. Next, the concept of *convergent biosignatures* will be introduced [1]. This term refers to independently evolved and potentially detectable organismic features of putative extraterrestrial life forms, and, more specifically, adaptations of such organisms that could be predicted on the basis of their repeated emergence on Earth. Ideally, such traits should be detectable without a detailed knowledge of the underlying molecular physiology.

The Emergence of Bioluminescence in the Ocean of Europa: Secondly, one obvious example of such a hypothesized convergent signature of life, bioluminescence, will be discussed within the context of Europa's oceanic environment. On Earth the repeated emergence of bioluminescence systems, mainly in marine organisms, occurred more than forty times in many branches of the tree of life, ranging from bacteria to complex animals such as fish and squid [3,4]. These systems employ a variety of underlying chemistries and evolved ca. 400 – 800 Mya ago as a mechanism for oxygen defense. At the core of every kind of bioluminescence lies a strictly oxygen-dependent biochemical reaction between a substrate (luciferin) and a taxon-specific enzyme (luciferase). One of the products of such a reaction is biologically produced, cold light. For the emergence of bioluminescence within the ocean of Europa a habitable environment is assumed in which: life originates rapidly from hydrogeological serpentinizing systems on the seafloor [5], evolves into chemoautotrophic forms, which, then, radiate into free-floating colonies, some of which might gain multicellular organization, able to harness energy gradients via ATP-like transduction mechanisms not commonly used by terrestrial life [6,7]. At some point during Europa's planetary history these pioneering organisms might encounter rising oxygen concentrations due to surface-ocean exchange of oxidants [8]. Various chemical systems could then be transformed into pathways for consuming ambient oxygen in bioluminescence-type reactions. Multicellular organisms, if present, could potentially even possess primitive visual systems deriving from infrared detecting sensory adaptations that emerged during hydrothermal system-centered evolution and development of complex life. This would be the major requirement for the co-opting of bioluminescence into a functional communication and signaling device.

Detection of Biological Light in Future Exploration: Lastly, it is described how bioluminescence, an unambiguous signature of life in an otherwise aphotic environment, either found in micro- or multicellular complex organisms, could be imaginably detected by an advanced AUV equipped with a space-mission adapted bathy-photometer or via biomimicry using the optical luring technique [9,10]. Prototype testing and calibration of this kind of instrumentation could conceivably be conducted at terrestrial analogues of Europa's subsurface ocean, for instance the sea below Antarctica or subglacial lakes.

References: [1] Chela-Flores J. (2003) *Int. J. Astrob., 2(4),* 307–312. [2] Conway Morris S. (2003) *Int. J. Astrob., 2(2),* 149–152. [3] Waldenmaier H.E., Oliveira A.G. and Stevani C.V. (2012) *Int. J. Astrob., 11(4),* 335–343. [4] Haddock S. H., Moline M.A. and Case J. F. (2010) *Ann Rev Mar Sci, 2,* 443–493. [5] Russell M. J., Nitschke W. and Branscomb E. (2013) *Phil. Trans. R. Soc. B, 368(1622).* [6] Schulze-Makuch D. and Irwin L. N. (2002) *Astrobiology, 2(1),* 105–121. [7] Irwin L.N. and Schulze-Makuch D. (2003) *Astrobiology, 3(4),* 813–821. [8] Hand K.P., Carlson R. W. and Chyba C. F. (2007) *Astrobiology, 07(6),* 1006–1022. [9] Widder E. A. et al. (1993) *Deep-Sea Res I Oceanog Res Pap, 40(3),* 607–627. [10] Widder E. A. (2007) *Oceanography 20(4),* 46–51.

THE H CHONDRITE HALITE PARENT BODY: WARM, WET, ORGANIC-RICH, RATHER HABITABLE AND POSSIBLY CERES.

M. Fries[1], S. Messenger[1], A. Steele[2], and M. Zolensky[1], [1]NASA ARES, Johnson Space Center, Houston, TX 77058 (marc.d.fries@nasa.gov), [2]Carnegie Institution for Science, Geophysical Laboratory, Washington, DC.

Introduction: Ancient halite grains are found in the H-chondrite meteorites Monahans and Zag, but these halites are exogenous to the H chondrite parent body as evidenced by inclusions within the halites. The original halite parent body (HaPB) must have been a warm, wet, organic-rich resident of the asteroid belt in order to accommodate the physical features of the halites. These characteristics fulfill all of the requirements for a habitable world. The dwarf planet Ceres has been proposed as the HaPB [1].

Discussion: *H Chondrite Halites:* The Monahans and Zag H-chondrite breccias both contain small (≤cm-scale), blue/violet grains of halite (NaCl) with minor sylvite (KCl)[2]. These halite grains contain minor, FeO-poor (forsteritic) olivine, pyroxene, feldspars, apatites, sulfides, magnetite, lepidocrocite (γ-FeO(OH), an oxide that forms when iron is immersed in water), metal grains, macromolecular carbon, light organic species, chlorine-substituted methane, and nanodiamond/graphite/carbonate assemblages (two of which have been found so far) [1]. This assemblage is inconsistent with H chondrite mineralogy, and the meteorite matrix immediately in contact with the halite is anhydrous. Therefore the halite grains originated elsewhere [3,4]..Measurements of multiple isotopic systems (Rb/Sr, ^{39}Ar/^{40}Ar, ^{129}Xe/I) indicate that the halite grains solidified in excess of 4.3 Ga ago [2,5,6], which provides a date for the ejection event from the HaPB to the H chondrite parent body (HPB). Cosmic ray exposure dating of Monahans indicates that it was ejected from the HPB 6.0±0.5 Ma ago [5]. Additionally, heating-stage experiments have shown that the brine inclusions have not been heated beyond 25°C [2]. Therefore, the HaPB-to-HPB halite transfer process was gentle, ergo their orbits must be similar.

Multiple authors have suggested that the asteroid Hebe is an attractive HPB candidate [8-11]. Comparison of the present-day orbits of Ceres and Hebe show that material could transfer between the two with impact velocities of ~1.20-1.38 km/s, and the possibility exists that this number was lower in the past [1]. The HPB and HaPB must be relatively dynamically similar in order to transfer material while retaining fluid inclusions in halite, and the combination of Ceres and Hebe as HaPB/HPB is dynamically reasonable.

Ceres as the HaPB: The hypothesis that Ceres is the HaPB is supported by multiple observations, namely that the HaPB must: 1) enable a low-energy transfer to the HPB, 2) have supported ~25°C brine as a source for halite >4.3 Ga ago, 3) contain abundant light organics and other carbonaceous phases that have been found in the halites. Additionally, the HaPB might have been a large body capable of assembling material from multiple sources. Ceres meets all of these requirements. Ceres is a carbonaceous body with water ice and/or hydration features detected in Earth-based observations [12,-14], and may be differentiated [12,13,15].

*Habitability of the HaPB: "*Habitability" can be defined as the availability of biologically important factors necessary for biology to arise and/or be sustained. The NASA Astrobiology Roadmap states that habitable environments "…must provide extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism." The HaPB must have featured liquid brine >4.3 Ga ago, contained light organics, and contained a suite of minerals in widely varying oxidation states (e.g. metal grains, lepidocrocite, magnetite) indicative of a chemical gradient and/or oxidation cycle. Furthermore, if we accept the hypothesis that the HaPB is Ceres, then evidence suggests the past presence of global scale aqueous processing and an internal heat source to support it [10,12]. These two factors supplement the "extended regions of liquid water", and "energy source" requirements for habitability.

References: [1] M. Fries *et al* (2013) 76th MetSoc, Abstract #5266. [2] Zolensky *et al* (1999) *Science* **285** 1377-1379. [3] Rubin *et al* 2002 *MAPS* 37:125-142. [4] J. Bridges *et al* (2004) MAPS **39** p. 657-666. [5] Bogard *et al* (2001) MAPS **36** 107-122. [6] Whitby *et al* (2000) *Science* **288** 1819-1821. [7] M. Gaffey and S. Gilbert (1998) MAPS **33**, 1281-1295. [8] W. Bottke *et al* (2010) DPS Meeting **42**, Abstract #1051. [9] M. Gaffey and S. Fieber-Beyer (2013) 76th MetSoc, Abstract #5124. [10] A. Morbidelli *et al* (1994) Astro.&Astrophys. **282** Abstract #955. [11] P. McCausland *et al* (2006) JRASC **100**, 104-113. [12] P. Thomas *et al* (2005) *Nature* **437**, p. 224-226. [13] B. Carry *et al* (2007) Astro.&Astrophys. **478** p. 235-244. [14] A. Rivkin *et al* (2006) *Icarus* **185** p. 563-567. [15] T. McCord and C. Sotin (2005) JGR **110** Abstract#E05009.

SURFACES AND EXOSPHERES OF THE ICY GALILEAN MOONS – AN INTEGRAL APPROACH.

A. Galli[1], A. Vorburger[1], P. Wurz[1], M. Tulej[1], N. Thomas[1], O. Mousis[2], S. Barabash[3], M. Wieser[3], and H. Lammer[4] [1]University of Bern, Physikalisches Institut, Switzerland (andre.galli@space.unibe.ch), [2]Observatoire des Sciences de l'Univers THETA de Franche-Comté, Besançon, France, [3]Swedish Institute of Space Physics, Kiruna, Sweden, [4]Austrian Academy of Sciences, Graz, Austria.

Introduction: The JUpiter ICy moons Explorer (JUICE) will investigate Jupiter and its system with particular emphasis on Ganymede as a planetary body and potential habitat. Europa and Callisto flybys will allow for a comparative picture of the icy Galilean moons [1]. As part of the scientific preparation work for JUICE, we examine the requirements and expected science results related to the Neutral gas and Ion Mass spectrometer (NIM), which belongs to the Particle Environment Package [2] on board JUICE.

Method: We follow an integral approach to characterize surfaces and exospheres of the icy Galilean moons. We combine new lab experiments with existing observations of exospheric species (e.g., [3], [4], [5], [6], [7]) and numerical modeling.

Results and Outlook: We have prepared 1D-models of the exosphere profiles at Europa, Ganymede, and Callisto (see Figure 1). The predicted densities allow us to verify and optimize the design of NIM. The next step is to transform the models to three dimensions. However, the physical and chemical properties of icy surfaces, in particular sputtering and sublimation parameters for icy regolith mixed with carbonates or salts, are not well known [8] and thus limit the general quality of exosphere models. The lab facilities at the university of Bern can accommodate a range of experiment setups with cold ice in vacuum. Currently, we perform irradiation experiments with pure water ice. In the coming years, we will expand the experiments to more complex cases (including UV-radiation, temperature cycles and chemical impurities such as O_2, C, S, CO_2, SO_2, and Na) relevant for Galilean moons. The results will constrain exosphere models and will enable the scientific community to better link exosphere measurements with processes in the ice and observed surface features.

References: [1] Grasset O. et al. (2013) *Planet. Sp. Sci., 78*, 1–21. [2] Barabash S., Wurz P., and the PEP team (2013) *EGUGA Conference Abstracts, 15*, Abstract # 9745. [3] Spencer J. R., Calvin W. M., and Person M. J. (1995), *JGR, 100*, 19049. [4] Brown M. E. and Hill R. E. (1996) *Nature, 380*, 229. [5] Noll K. S., Johnson R. E., Lane A. L., Domingue D. L., and Weaver H. A. (1996) *Science, 273*, 341. [6] Hall D. T., Feldman P. D., McGrath M. A., and Strobel D. F. (1998) *ApJ, 499*, 475. [7] Carlson R. W. (1999) *Science, 283*, 820. [8] Johnson, R. E., Carlson R. W., Cooper J. F., Paranicas C., Moore M. H., and Wong M. C. (2004) *"Jupiter. The planet, satellites and magnetosphere"*, 485 – 512, Eds. Bagenal F., Dowling T. E., McKinnon W. B., Cambridge planetary science, Vol. 1, Cambridge, UK: Cambridge University Press, ISBN 0-521-81808-7.

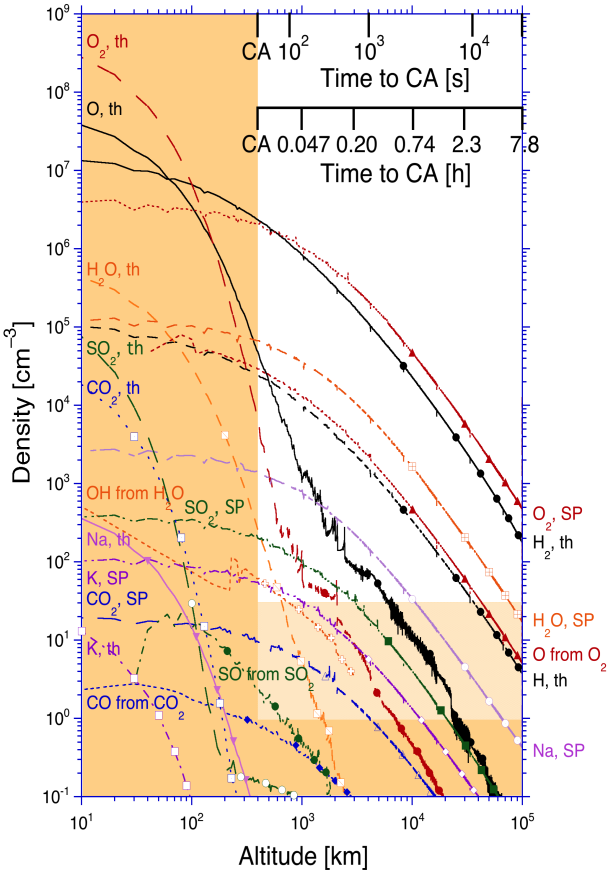


Figure 1: Exosphere density profiles predicted for Europa. The time tags in the upper right indicate the duration of expected JUICE observations around the closest approach (CA) of the flyby. The expected minimum altitude and the sensitivity of NIM define a range of detectable exospheric species (white area).

TERRESTRIAL ANALOGS FOR DETECTION AND CHARACTERISATION OF OUTFLOW FROM POTENTIALLY HABITABLE ZONES WITHIN ICE SHELLS OF ICY WORLDS.

D. F. Gleeson[1], [1] Centro de Astrobiología, CSIC–INTA, Torrejon de Ardoz, Madrid, Spain, (dgleeson@cab.inta-csic.es).

Introduction: On the surface of Europa, non-ice materials are concentrated along geologic features [1, 2] and could represent sites of outflow from deeper within the shell. Areas of partial melt or fluid circulation within the ice shells of this and other icy worlds could represent potentially habitable zones for microbiology.

On the Earth icy environments with active hydrology can deposit precipitates when concentrated fluids out of equilibrium with the exterior environment access the surface. This can generate a mineralogical signature reflecting the chemistry of the subsurface hydrological system. Borup Fiord Pass on Ellesmere Island in the Canadian High Arctic, and Blood Falls in the Taylor Valley, Antarctica are examples of two sites where varying chemistries of subsurface fluids have generated unique signatures on glacial ice.

Exploring how these mineral deposits are expressed in hyperspectral satellite data may allow us to refine our ability to detect and characterise supraglacial outflow from orbit and remotely characterise subsurface icy habitats.

Figure 1. Top: sulfur-rich deposits of Borup Fiord Pass, bottom: iron-rich deposits of Blood Falls.

Methodology: Mineral deposits associated with the outflow of subsurface fluids onto ice can contrast strongly with their surroundings, generating geochemical signatures which can be detected in satellite datasets [3, 4]. Field spectra of *in situ* materials, where available, can provide appropriate detection targets for spectral searches. Hyperspectral satellite data from the Hyperion instrument onboard EO-1 provide a means of detecting and characterising geochemical signatures of mineral deposits associated with outflow of subsurface hydrological systems.

Discussion: Successful detections of widely varied mineral signatures associated with surface outflow in satellite datasets of Arctic and Antarctic regions demonstrate the potential of this technique as a tool for remote detection and characterization of subsurface systems.

Exploration of terrestrial sites where the geochemistry and consequent habitability of subsurface hydrologic systems can be probed from orbit can prepare us for preliminary habitability evaluations of sites at Europa and other icy worlds. Orbital measurements will be a necessary precursor to any *in situ* investigations at Europa and information gained from orbit can refine our ability to select appropriate landing sites for detailed investigation.

References:

[1] McCord, T. B. et al. (1999). *JGR - Planets*, 104, 11827-11851. [2] Carlson, R. W., Johnson, R. E., & Anderson, M. S. (1999) *Science*, 286, 97-99. [3] Gleeson, D.F. et al. (2010) *Remote Sensing of Environment*, 114, 1297-1311. [4] Thompson, D., et al. (2012) *Transactions on Geoscience and Remote Sensing* Volume PP, Issue 99, 1-13.

STRUCTURE AND DYNAMICS OF GANYMEDE: IMPLICATIONS FOR ITS POTENTIAL HABITABILITY.

O. Grasset[1], [1]1Planetology and Geodynamics, University of Nantes, CNRS, France; olivier.grasset@univ-nantes.fr.

Introduction: Ganymede is the largest moon of the Solar System, with great relevance to astrobiological studies because it satisfies a large number or prerequisites for habitability. A review of its properties, especially regarding its habitability will be given.

Main characteristics of the moon: Ganymede is the largest satellite in the Solar System (2631 km in radius). In the Jovian system, it holds a key position because it features old, densely-cratered terrain, similar to most of Callisto's surface, but also widespread tectonically resurfaced regions, resembling a large part of Europa's surface. Ganymede displays a wide range of surface ages, which reveal a geological record of several billions of years, and a great variety in geological and geomorphic units. These features are the surface signature of internal heat release during Ganymede's evolution. Ganymede is also the only satellite and -with Mercury and the Earth- one of only three solid bodies in the Solar System that generate a magnetic dipole field at the present time. A description of our current knowledge of Ganymede's characteristics can be found in Grasset et al.[1], and references therein. As indicated by its small moment of inertia factor of 0.3115, Ganymede is a highly differentiated body. Interior structure models consistent with the gravity field, bulk density, and magnetic constraints include (i) an iron-rich core (at least part of which being liquid to generate the intrinsic magnetic dipole field), (ii) a silicate shell, (iii) an hydrosphere which may be at least 500 km thick (about 50 %wt.), and a very tenuous atmosphere[2-4]. The composition of the atmosphere includes O, O_2, and possibly ozone (O_3) [5-6].

Potential habitability of the liquid reservoirs in Ganymede: Two kind of habitable zones should be considered: a deep and global liquid layer, and also shallow liquid reservoirs in the icy crust. On Ganymede, the hydrosphere must be split into a high-pressure ice layer consisting of various water-rich high-pressure ices denser than liquid water, the subsurface water ocean, and an ice-I layer forming the outer crust of the satellite. The liquid layer could be up to 100 km thick. It has been suggested that the depth of the ocean should be close to 150 km[2]. Chemical and energy exchanges between the rocky layer and the ocean at present, which are crucial for habitability, cannot be ruled out but imply efficient transport processes through the thick high - pressure icy layer. Such processes are indeed possible[3] but not as clear-cut as the exchanges envisaged for Europa and that probably prevailed until recent times.

Based on Galileo data, there is no evidence of present activity, or recent features which could suggest the existence of shallow reservoirs. No evidence for recent cryovolcanic resurfacing is identified thus far. However, locally restricted scalloped depressions called paterae adjacent to Ganymede's bright terrain, which could represent caldera-like features[7] are interpreted as cryovolcanic features that appear in Ganymede's past history. In fact, the geologic record on Ganymede does not support the existence of shallow liquid reservoirs at present. Still, these occurrences cannot totally be ruled out because most of the Galileo data was acquired at medium spatial resolution, impeding the detection of small features.

Conclusions: Following Galileo's discovery 400 years ago of the Galilean satellites, our knowledge of the large icy moons within our Solar System has continued to grow. On Ganymede, Galileo has demonstrated that the largest moon of our solar system is of strong interest as a planetary body and also as a potential habitat. That is why the ESA JUICE mission will go in orbit around the moon after a tour of three years in the Jovian system. It is the necessary step to characterise this remarkable moon and to explore in details its potential habitability.

References:

[1] Grasset O. et al. (2013) *Planet. Space Sci.*, 78, doi: 10.1016/j.pss.2012.12.002.
[2] Kivelson, M.G. et al. (2002) *Icarus* 157.
[3] Sohl F et al. (2010) *Space Sci. Rev.*, 153.
[4] Anderson J. D. et al. (2001) *Icarus*, 153 (1).
[5] Hall D. et al. (1998), *Astroph. J.* 99.
[6] Noll K.S. et al. (1996) *Science* 273.
[7] Stephan K. et al. (2013) *Astroph. Sp. Sci. L.*, 356.

EUROPA LANDING SITE SELECTION SUPPORTED BY ICE PENETRATING RADAR. C. Grima[1], D. M.. Schroeder[1], D. D. Blankenship[1], and D.A. Young[1]. [1]University of Texas at Austin Institute for Geophysics, J. J. Pickle Research campus, Bldg.196, 10100 Burnet Rd., Austin TX 78758, USA. cyril.grima@gmail.com

Introduction: The shape and composition of the surface of Europa result from multiple processes, most of them involving direct and indirect interactions between the liquid and solid phases of its outer water layer [1, 2]. The surface ice composition and chemistry reflect the material exchanged with the sub-glacial ocean and potentially holds signatures of organic compounds that could demonstrate the life sustainability of the icy moon [3]. Therefore, these places are considered primary targets for in-situ landing missions with a very high science potential [4], but they are mostly located in complex terrains disrupted by exchange mechanisms with the ocean/lenses of sub-glacial liquid water [5, 6]. In the scope of a landing site selection process to ensure a safe delivery of a future lander, the next missions to Europa will have to characterize the surface roughness. Planetary surface roughness is usually derived from point-to-point elevation models acquired by laser altimetry or stereo-imagery [7]. Together these techniques provide surface composition/density, topography, roughness and rock abundance information [8]. However, a complete instrument package is rarely available and the extant subset is often miss-matched in terms of coverage, resolution and sensitivity.

In the last decade, nadir-looking penetrating radars have become another remote-sensing technology commonly used for planetary surface and sub-surface exploration [e.g. 9, 10]. A multi-frequency (9-20 MHz) Ice Penetrating Radar (IPR) is a primary instrument in the strawman scientific payload of the NASA's Europa Clipper mission concept that has a reconnaissance objectif assigned for a follow-on lander.

Method: We propose a novel radar sounder analysis technique, the Surface Statistical Reconnaissance (SSR), to quantitatively characterize the roughness of icy worlds at relevant scales for potential landing sites and to constrain their surface composition/density. Our approach makes use of surface echo amplitude distributions collected along orbits by successively fitting them with a statistical envelope and a backscattering model dependent on the surface permittivity and roughness.

We demonstrate the reliability of the SSR technique with an application to a radar dataset acquired during the 2004-05 austral summer campaign of the Airborne Geophysical Survey of the Amundsen Sea Embayment, Antarctica, (AGASEA) project with the High-Capability Radar Sounder (HiCARS, 60 MHz) system operated by the University of Texas Institute for Geophysics (UTIG). The covered region (Thwaites catchment, West Antarctica) exhibits with a large set of various terrains (smooth wind-eroded surfaces, crevasse fields and ice matrix analog to Europa chaos, see figure below). Results are compared with simultaneously acquired laser altimetry and nadir imagery of the surface. We emphasize the possibilities and advantages of the method in the light of the future exploration of Europa and Ganymede icy moons by multi-frequency ice penetrating radars.

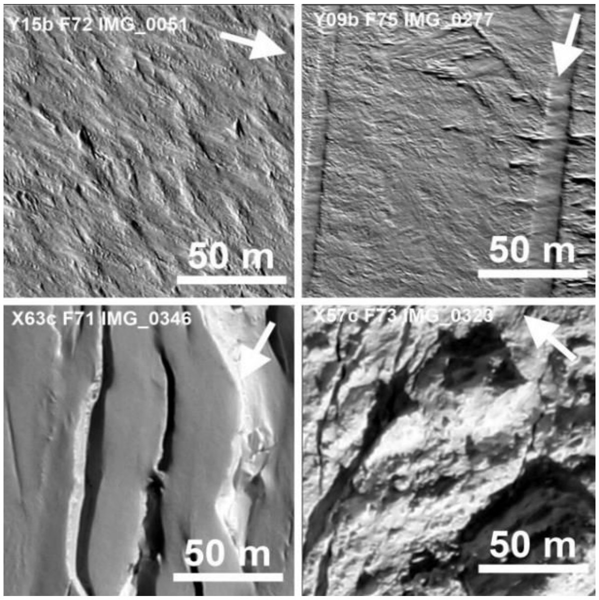


Figure. Four pictures from nadir imagery illustrating different kind of surface terrains studied in Antarctica as Europa analogs for roughness. A white arrow indicates direction of lightning for each scene. Tones were optimized to emphasize the surface texture.

References: [1] Kattenhorn S.A. and Hurford T. (2009). In *Europa*, The Univ. of Arizona Press. [2] Collins G. and Nimmo F. (2009), In *Europa*, The Univ. of Arizona Press. [3] Hand K. P. (2009), In *Europa*, The Univ. of Arizona Press. [4] Pappalardo R T. et al. (2013) *Astrobiology, 13(8)*, 740-773. [5] Schenk P. M. (2009) *Geo. Res. Let., 36(15)*. [6] Ivanov M. A. (2011) *Adv. in Space Res., 48(4)*, 661-677. [7] Ball A. J. (2007) *Cambridge Univ. Press.* [8] Golombek M. P. et al. (2012), *Sp. Sci. Rev.* 170, 641-737. [9] Picardi G. et al. (2005) *Science*, 310(5756), 1925-8. [10] Seu R. et al (2007), *J. of Geo. Res.*, 112(E5), 1-18.

SURVIVAL AND CHEMISTRY OF ORGANICS ON THE NEAR SURFACES OF EUROPA AND TITAN.

Murthy S. Gudipati[1], Antti Lignell[1],[2], Irene Li Barnett[1], Isabelle Couturier-Tamburelli[3], Ronen Jacovi[1,4], Benjamin Fleury[5], Nathalie Carrasco[5]. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, gudipati@jpl.nasa.gov; [2]Present Address: Arthur Amos Noyes Laboratory of Chemical Physics, California Institute of Technology, Pasadena, CA 91125, USA; [3] Aix-Marseille Université, laboratoire Physique des interactions ioniques et moléculaires, 13397 Marseille cedex 20 France; [4]Present Address: Flight Control Group, Urban Aeronautics LTD, Nahal-Snir 10, Yavne, 81224, Israel; [5]Laboratoire Atmospheres, Milieux, Observations Spatiales (LATMOS), Université de Versailles Saint-Quentin-en-Yvelines, France.

Introduction: While habitability is the probability of life to survive and thrive should it exist, habitable environments should provide favourable conditions for life to thrive. These include a balance of chemical reaction potential – not too severe to destroy and not too low to deprive life in question. Our interest in the context of habitability of icy worlds is of twofold. One to determine whether the organic precursors or metabolites of life can survive on radiation rich icy surface such as Europa, and the second to investigate whether low-radiation environment of Titan's lower atmosphere and surface can still harvest photons converting photon-energy into chemical-energy. Except Mars, many solar system bodies have severe surface conditions (temperature, pressure, etc.) non conducive for life. However, they could potentially have habitable environments such as subsurface liquid reservoirs [1]. Exchange of material between the surface and subsurface [2] will play a key role in both habitability and detectability of life in these places.

Europa: Recently we conducted quantitative analysis of electron induced damage depths of aromatic hydrocarbons in ices [3]. By using the polycyclic aromatic hydrocarbons (PAHs) as surrogates for biomolecules, we found that these organics undergo chemical modifications at farther depths than what the primary electrons could penetrate. We attributed this behavior to the secondary radiation (photons) generated during the impact of the primary energetic particle on ice. The effect of secondary photon radiation has not been taken into account until now. Added to this another aspect of organics in icy environment that was discovered earlier: lower ionization energy of organics in ices [4], plays an important role in extending the damage farther than otherwise expected by the primary impacting particles. We will discuss the consequence of these laboratory studies on near-surface survivability of organics on Europa – critical for detection of life or biomolecules, if exist – from remote sensing.

Titan: Chemistry on Titan is known to be driven by ultraviolet photons and solar wind in its upper atmosphere [5] and essentially no chemical activity in its lower atmosphere or on the surface, except for cosmic ray penetration to the surface [6] and tidal forces in the interior [7, 8]. However, Titan's lower atmosphere received photons [9] with spectral distribution somewhat similar to Earth's (maximizing at ~500 nm) but several orders of magnitude lower flux. Hence, photochemical processes similar to that occur on Earth's surface could occur on Titan's lower atmosphere and surface [10] as well – only taking several orders of magnitude longer to compensate the flux differences. We have shown recently that indeed such photochemistry could occur in Titan's atmosphere taking condensed-phase properties of Titan's organic molecules. Most of the biomolecules on Earth are tuned to absorb at the maximum of solar flux (400 – 700 nm) and such molecules could be made on Titan in its atmosphere and rain down to the surface. We will discuss the scenarios of synthesis of complex biologically relevant molecules on Titan's surface.

Acknowledgments: This work was funded by NASA through Astrobiology Institute (Titan, Icy Worlds, and Early Habitable Environments). This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References:

1. Schmidt, B.E., et al., Nature, 2011. **479**(7374): p. 502-505.
2. Brown, M.E. and K.P. Hand, Astronomical Journal, 2013. **145**(4).
3. Barnett, I.L., A. Lignell, and M.S. Gudipati, Astrophysical Journal, 2012. **747**(1): p. L24.
4. Gudipati, M.S. and L.J. Allamandola, Astrophysical Journal Letters, 2004. **615**: p. L177-L180.
5. Teanby, N.A., et al., Nature, 2012. **491**(7426): p. 732-735.
6. Zhou, L., et al., Astrophysical Journal, 2010. **718**(2): p. 1243-1251.
7. Sohl, F., et al., Journal of Geophysical Research-Planets, 2003. **108**(E12): p. 13.
8. Tobie, G., A. Mocquet, and C. Sotin, Icarus, 2005. **177**(2): p. 534-549.
9. Karkoschka, E., Planetary and Space Science, 2012. **60**(1): p. 342-355.
10. Lunine, J.I. and S.M. Horst, Rendiconti Lincei-Scienze Fisiche E Naturali, 2011. **22**(3): p. 183-189.

SPECTRA OF LOW-TEMPERATURE CHLORINE SALT HYDRATES AND IMPLICATIONS FOR EUROPA.

J. Hanley[1], J. B. Dalton III[2], V. F. Chevrier[3], C. S. Jamieson[4]. [1]Southwest Research Institute, Boulder, CO 80302, [2]JPL/Caltech, Pasadena CA 91011, [3]Arkansas Center for Space and Planetary Science, University of Arkansas, Fayetteville, AR 72701, [4]SETI Institute, Mountain View, CA 94943; jhanley@boulder.swri.edu.

Introduction: Chlorine is expected to exist throughout the solar system and would be present on any body that has chondritic origins. Chlorine ions and their associated salts (e.g. chlorides (Cl^-), chlorates (ClO_3^-) and perchlorates (ClO_4^-)) would in turn occur on any body that has been altered by water in the past, and they are important to the stability of water. Chlorine salts lower the freezing point of water, allowing it to be liquid down to ~204 K [1].

If found on the surface of Europa, chlorine salts would serve as a window to the interior, and support the existence of a liquid ocean beneath the icy crust. If there is chlorine in the system, as models predict [2], chloride salts would be likely to form. Chlorides and (per)chlorates may also be produced by radiolysis of Iogenic Na, Mg and Cl. Recent studies have suggested that magnesium is originally brought to the surface as magnesium chloride [3].

However, none have been identified on Europa's surface in the near-infrared (NIR) by Galileo's NIMS or New Horizon's LEISA. This is primarily because most spectral libraries contain only anhydrous, high temperature "Earth-relevant" chlorides, and virtually no perchlorate data. Given the abundance of water on Europa's surface, any chlorine salts would be expected to be present in a highly hydrated form. Furthermore, the low surface temperature of Europa is likely to effect the many temperature-dependent spectral features [4], particularly of water (including that of hydration).

Reference spectra of surface materials at relevant temperatures are critical for deriving abundance estimates through spectral modeling. Therefore, we measured the spectra of various chlorine-salt hydrates at 296 and 80 K. Our study alleviates the lack of data in current spectral libraries for hydrates that exist on Europa and other planetary surfaces [5]. We suggest that it may be possible to identify chlorine salts on the surface of Europa, given the similarities of hydrated chlorine spectra to ice and other hydrated salts, such as sulfates.

Results and Discussion: We show that hydrated $MgCl_2$ salts exhibit many diagnostic features, especially at low temperature (Fig. 1), that could aid in their future detection. (Per)chlorate salts' spectra behave similarly: the main features in the NIR are due to water of hydration, and at low temps they become narrower and more well-defined [5]. This data would also be relevant to other icy bodies in the outer solar system, such as Iapetus, Enceladus, and Pluto, among others.

Additionally, when mixed with water at eutectic concentrations, chloride salts do not significantly alter the main spectral bands seen in pure water ice [5], even though they form a hydrated phase; however, the bands do appear broader than for those of pure water ice. When comparing to the Galileo NIMS spectrum of the "dark material," the general shape is similar: most of the spectral structure arises from the water molecules, whether as ice or hydrates. Though weaker than the main H_2O bands, fine structure is apparent in the NaCl and $MgCl_2$ brine spectra, which could prove diagnostic.

Implications for Life: Life as we know it does not thrive at low water activity (aH_2O). The lowest known tolerance is $aH_2O = 0.61$ [6], whereas chlorine salts reach as low as 0.5 [1]. Detecting chlorine salts on the surface of Europa would argue for a colder and lower activity ocean, limiting the type of life that might be found there. However, halophiles are well adapted to relatively low aH_2O. Photosynthetic cyanobacteria were found within crusts of halite [7],which can scatter UV-light while allowing photosynthetically active radiation [8]. In Antarctica's Lake Vida, bacteria are metabolically active at low temperatures and high salt concentrations [9]. These examples demonstrate that biologic activity at low temperatures and low activities is not unheard of even on Earth, suggesting that life might be able to survive throughout the solar system.

References: [1] Hanley, J., et al. (2012) *GRL*, *39*, L08201. [2] Kargel, J.S., et al. (2000) *Icarus*, *148*, 226-265. [3] Brown, M.E. and K.P. Hand (2013) *ApJ*, *145*, 110. [4] Dalton, J.B., III, et al. (2005) *Icarus*, *177*, 472-490. [5] Hanley, J., et al. (2013) *JGR, under review*. [6] Grant, W.D. (2004) *Phil.Trans. Roy. Soc. London*, *359*, 1249-1267. [7] Wierzchos, J., et al. (2006) *Astrobio.*, *6*, 415-422. [8] Cockell, C.S. and J.A. Raven (2004) *Icarus*, *169*, 300-310. [9] Murray, A.E., et al. (2012) *PNAS*, *109*, 20626-20631.

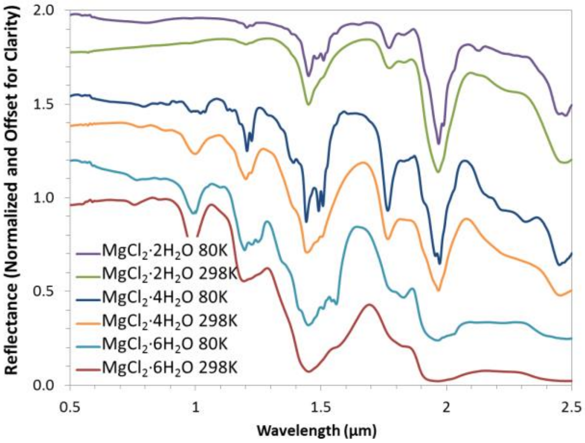


Figure 1. NIR reflectance spectra of various hydrates of $MgCl_2$ at 296 K and 80 K [5]. Note how spectral features become more enhanced at very low temperature.

TRITON – WARM PLUMES OR COLD JETS?

C. J. Hansen[1], F. Nimmo[2], J. Spencer[3], H. Hammel[4], [1]Planetary Science Institute, Tucson, AZ, cjhansen@psi.edu; [2]University of California, Santa Cruz, CA; [3]Southwest Research Institute, Boulder, CO; [4]AURA, Washington, DC .

Introduction: Triton's young surface with relatively few craters stands out among moons in the solar system and puts it in a class with Io, Europa, Titan and Enceladus – other moons with active surface processes today. Craters have likely been erased by surface yielding, deformation and viscous relaxation. New models of the interior suggest that heating is ongoing and could not be a remnant from Triton's capture into orbit around Neptune [1].

Voyager detected particulate plumes rising 8 km above the surface [2]. Dark fans deposited on the surface were attributed to deposits from similar, no-longer-active plumes, as shown in Figure 1. The Voyager imaging team immediately noted the similarity to fans seen seasonally in Mars' southern polar region and the plumes were subsequently modeled as solar-driven expulsions of nitrogen carrying particles entrained from the surface [3, 4]. We now have another possible comparison, with the Cassini discovery that Enceladus spews water vapor and ice particles from fissures across its south pole [5, 6].

Triton's warm interior: Triton's surface age of <100 MY is derived from the lack of craters on its surface [7]. A liquid mantle was first suggested as a result of Triton's capture into orbit around Neptune [summarized in 8]. Later work showed that with a sufficient ammonia component a liquid layer could persist to present time [9]. The new models of the interior of Triton show that the combination of radiogenic heating with tidal heating due to Triton's obliquity could sustain a long-lived subsurface ocean, and sluggish convection, even without invoking substantial ammonia [1].

Source of the plumes: But do Triton's plumes come from the subsurface ocean? Are they more like Enceladus or the seasonal gas jets of Mars?

Eruption from the interior – the Enceladus analogy. Recent work on Enceladus gives a source size of 9 m [10], with vapor exiting at speeds up to 1-2 km/sec [11], consistent with the postulate that warm vapor from a subsurface ocean exits through a nozzle-like opening to the surface. Triton's plumes reach 8 km altitude, erupting through an ambient atmosphere, before being carried away horizontally by the ambient wind. Although this can be achieved with solar-driven plumes, perhaps Triton's eruptions come from a deeper source.

Solar-driven activity – the Mars analogy. The discovery of the fans and plumes on Triton actually inspired the solar-driven model for the fan-shaped deposits imaged on Mars [12]. This model postulates that gas from basal sublimation of a seasonal ice layer is trapped beneath impermeable translucent ice. Eventually when the pressure is high enough the ice will rupture and the gas will escape, entraining surface particles. Mars and Triton are similar in that their volatiles are mobile (CO_2 for Mars and N_2 on Triton) and will form seasonal caps. The detection of plumes by Voyager in late southern spring is consistent with the timing expected for solar-driven jets.

Implications for habitability: The existence of life in Triton's subsurface ocean is the subject of science fiction with what we know today. We can however consider the implications for detection of life being expelled from the interior by analyzing data we have and what we might conceivably collect in the future. To this end we compare and contrast plumes on active bodies.

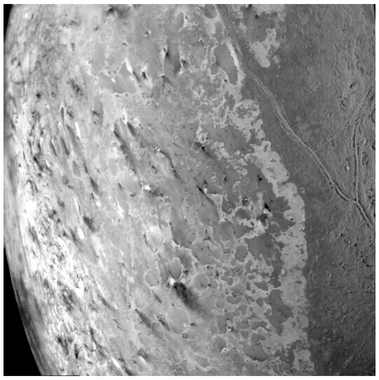


Figure 1. *Dark fans of material are deposited across the south polar region of Triton in this Voyager image. Both of the active plumes can be seen rising from the surface, then being bent by ambient winds.*

References: [1] Nimmo, F. and J. Spencer (2013) submitted to Icarus. [2] Smith et al. (1989) *Science, 246,* 1422-1450. [3] Soderblom, L. et al. (1990) *Science, 250,* 410-415. [4] Kirk, R. L. et al. (1990) *Science, 250,* 424-428. [5] Hansen, C. J. et al. (2006) *Science, 311,* 1422-1425. [6] Porco, C. et al. (2006) *Science 311,* 1393-1400. [7] Schenk, P. and K. Zahnle (2007) *Icarus, 192,* 135-149. [8] McKinnon, W. et al. (1995) in *Neptune and Triton,* ch. 17. [9] Hussmann, H. et al. (2006) *Icarus, 185,* 258-273. [10] Goguen, J. et al. (2013) *Icarus, 226,* 1128-1137. [11] Hansen, C. J. et al. (2011) *GRL, 38,* L11202. [12] Kieffer, H. H. et al. (2006) *Nature 442,* 793-796.

Techniques for the in situ analysis of Titan lake fluids. R. Hodyss[1], M.J. Malaska[1], P.M. Beauchamp[1], [1]Jet Propulsion Laboratory, California institute of Technology, Pasadena, CA 91109

Introduction: Titan's lakes are a primary target for future Titan exploration, and serve as a nexus for the complex chemical interchanges between the surface and the atmosphere. The lakes are a repository for the products of atmospheric chemistry, interconnecting Titan's geology, atmosphere, and astrobiological potential. Detailed chemical analysis is a goal of any mission to the lakes. Standard organic analysis techniques, such as gas chromatography (GC) and mass spectrometry (MS), require acquisition and transfer of a sample to the analytical instrument. The GC is problematic because of the potential for clogging and the additional complexity of transferring, without significant alteration, a 94 K liquid methane/ethane sample into the warm interior of a spacecraft. Volatilization, exsolvation and fractionation are major obstacles to overcome. We present two successfully tested in situ methods to analyze Titan lake fluids to overcome these obstacles: 1) the use of spectroscopic fiber optic probes, and 2) the use of solid phase micro-extraction (SPME) fibers for preconcentration of analytes from cryogenic fluids.

Fiber Optic Probes: Fiber optic probes have a number of advantages for in situ analysis. By using both ultraviolet (UV) and infrared (IR) spectroscopic probes, various chemical classes can be targeted with high sensitivity. Ultraviolet spectroscopy is ideal for analysis of trace dissolved aromatic compounds such as benzene, but is blind to the bulk components of the lakes, such as ethane. Mid-infrared spectroscopy is useful for analyzing the bulk components though analysis of the CH stretching features, and can detect astrobiologically interesting components such as compounds with carbonyl and nitrile funtionalities.

We have successfully tested these technques in the laboratory. Two different fiber optic immersion probes were used, one optimized for the UV and visible, the other for the mid-IR. The probes are interfaced to commercial IR and UV spectrometers and the appropriate light sources. Solutions of liquid methane and ethane at Titan surface temperatures (94 K) are prepared, and the solute is introduced as a liquid or a solid. The solution is stirred to ensure dissolution, and the fiber probe is then immersed in the liquid solution. Fig. 1 shows infrared spectra obtained with the infrared probe.

We will present results for several different solutes representing aromatics, hydrocarbons and oxygenated compounds, in both the ultraviolet and mid-infrared. Estimates of the limits of detection for various species will also be presented.

Solid Phase Microextraction (SPME): SPME fibers are used to extract and *concentrate* analytes from liquids by adsorption into a polymer matrix bound to a silica fiber. By adjusting the polarity of the coating material, it is possible to selectively absorb different analytes. After adsorbtion, the fiber is heated to release the analyte, which can then be analyzed by standard techniques, such as gas chromatography or mass spectrometry.

SPME fibers have a number of advantages for in situ chemical analysis. They are small, lightweight, and rugged. They can be general or tuned to select for the analytes of interest. SPME fibers can be interfaced to several different analysis techniques, including MS, GC and liquid chromatography.

In a typical experiment, SPME fibers were immersed for 1-10 minutes in stirred solutions of various organics in liquid ethane at 94 K. The fiber was withdrawn from the solution and allowed to warm to room temperature, before analysis by MS using an SRS 200 quadrupole MS with electron impact ionization. Figure 2 shows some initial results from a solution of benzene in liquid ethane using an 85 µm Carboxen/PDMS fiber that was exposed to the solution for 10 minutes. Immediately after insertion of the fiber into the mass spectrometer system, a prominent signal appeared at 78 m/z, corresponding to benzene.

We will present results for several different solutes representing functional groups of interest on Titan using a range of fiber types.

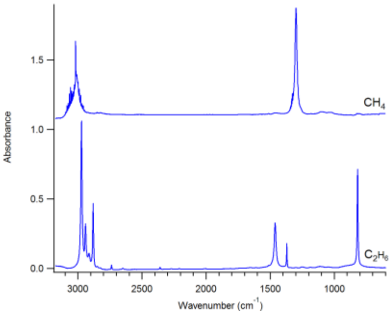


Fig. 1 IR spectra of liquid methane and ethane at 94K.

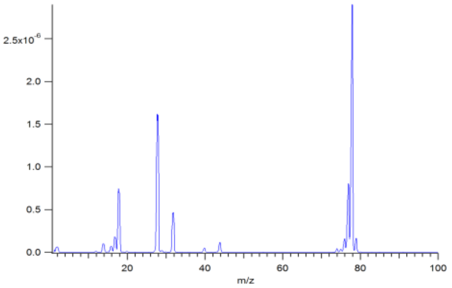


Figure 2. Mass spectrum of benzene desorbed from a Carboxen/PDMS SMPE fiber.

Silica nanoparticles provide evidence for hydrothermal activities at Enceladuas. H.-W. Hsu[1], F. Postberg[2,3], Y. Sekine[4], S. Kempf[1], M. Horányi[1], A. Juhász[5,1], R. Srama[3], [1]LASP, University of Colorado, Boulder, Colorado 80303, USA, [2]Institut für Geowissenschaften, Universität Heidelberg, 69120 Heidelberg, Germany, [3]IRS, Universität Stuttgart, 70569 Stuttgart, Germany, [4]Dept. of Complexity Sci. & Engr., University of Tokyo, Kashiwa 277-8561, Japan, [5]Institute for Particle and Nuclear Physics, Wigner RCP, 1121, Budapest, Hungary

Introduction: The plume of water vapour and ice particles emitted from warm fractures ('tiger stripes') near the south pole of Saturn's small, icy moon Enceladus is assumed to emerge from shallow subsurface liquid water which previously was in contact with rocky material probably in an ocean at much greater depth [1,2,3,4]. While measurements by Cassini instruments provided evidence for subsurface water, conditions of the ocean, such as the temperature, pH-value, and possible water-rock interactions, can only be poorly constrained by theoretical considerations and modeling [4,5]. Here we show that the nanodust stream particles [6] detected by the Cassini spacecraft in the Saturnian system consist mainly of silica (SiO_2), indicating current or near-past high temperature water-rock interactions at their source - Enceladus. The measured properties of stream particles suggest that they form in moderate basic (pH = 8-10), hydrothermal waters with moderate salinity (< 0.5 M) when the fluid temperature decreases from at least ~ 100°C to ~ 0°C [7,8]. The process was reproduced by hydrothermal laboratory experiments [7]. These findings rank stream particles as the first samples of current or geologically recent hydrothermal activity outside the planet Earth.

References:

[1] Postberg, F. et al. (2009) Nature, 459, 1098-1101. [2] Postberg, F. et al. (2011) Nature, 474, 620–622. [3] Schmidt, J. et al. (2008) Nature, 451, 685-688. [4] Spencer, J. R. et al. (2009) , Enceladus: An active cryovolcanic satellite in Saturn after Cassini-Huygens, Astrophysics and Space Science Library of Springer Vol. 385 (eds. Doughetry, M., Esposito, L., and Krimigs, S.), p. 683-724. [5] Zolotov, M. Y. (2007) GRL, 34, L23203. [6] Kempf, S. et al. (2005) Nature, 433, 289-291. [7] Sekine, Y. et al. (to be submitted). [8] Ogasawara, Y. et al. (2013) Geochim. Cosmochim. Acta, 119, 212-230.

Local Topographic Shielding and Radiation Shadows from Electron Irradiation on Europa.

T.A. Hurford[1] and J.F. Cooper[1] and C. Paranicas[2] and R. Greenberg[3] and S.J. Sturner[1], [1]NASA Goddard Space Flight Center, [2]John Hopkins Applied Physics Lab. [3]University of Arizona.

Introduction: A torus of magnetically trapped high-energy electrons and ions encompasses Jupiter, extending from inside the orbit of Io out to Ganymede's orbit. At Europa's orbital radius the density of these particles is especially high and Europa experiences a continuous bombardment of its surface by these energetic particles. The high radiation of energy into its surface makes it unlikely that simple organisms can survive on its surface and also drives chemical and physical processing of the surface [1,2].

While the source of charged particles in Jupiter's magnetosphere can be described as an isotropic, the motions of these particles and their interaction with the icy satellites such as Europa lead to natural asymmetries in the population of charged particles impacting its surface.

The motion of energetic electrons in Jupiter's magnetic field lead to natural asymmetries in the flux of these particles on Europa's surface. In this paper, we first describe the anisotropic flux of energetic electrons bombarding Europa's surface as defined by the processes detailed above. We then look at how topography in general can shield the surface from these energetic electrons. Finally, using the limited data from the Galileo spacecraft we look for the best places to observe this effect.

Topographic Shielding: Based on the anisotropic nature of the energetic electrons impacting the surface of Europa, surface geology might block significant amounts of radiation. This may allow portions of the surface to experience a relatively benign radiation environment. In order to look at the effect of geology on shielding the surface, we first look at the ability to block radiation from large-scale structure such as craters, pits and ridges. We then look to the effect of non-flat surfaces on radiation levels.

Craters and Pits. While Europa's surface is geologically young, <100 Myr old [3], its surface does record the most recent of impactors to strike Europa. These craters are a negative relief on the surface with rims and the interior of these features see a restricted portion of the sky. The zenith angle visible from the floor of a crater can be represented as a function of the crater's depth and diameter. Pits are another type of negative relief features on Europa. These topographic lows represent of subsidence of the surface. While the edges are not raised with respect to the surrounding terrain, pits like craters can restrict the view of the sky while within them. However, the depths of these features are shallow compared to their diameters, leading to very little shielding from energetic electrons.

Ridges. The most common type of positive relief features on Europa are ridges often referred to as double ridges due to their morphology in which two raised ridges run down the length of a central crack. These features are typically a few km in width and can extend from a few kilometers in length to 1000s of kilometers. While iconic images of ridges, such as Androgeos Linea give these features the appearance of large amounts of relief on the surface, ridges are typically only a few 100s of meters in height. In the trenches flanking a ridge most of the sky is visible from its floor and the far horizon is practically visible in the direction away from the ridge. Thus, the ridge does not provide significant shielding from radiation.

Tilted Surfaces. While flat surfaces in craters or along flanks of craters do not receive enough shielding from energetic electron bombardment, tilted surfaces may limit exposure. The most extreme tilt the surface can experience is vertical tilt or cliff face as seen in plates in Conamara Chaos. These tilted surfaces can restrict their radiation exposure and if facing an opposite cliff face can experience no radiation exposure.

Microgeology. Small-scale geology such as boulders, especially on tilted surfaces can also provide limited regions of no to low radiation exposure. While imagery currently cannot assess actual sites of small-scale shielding, we describe the conditions and locations most likely to lead to shielding from energetic electrons.

Conclusions: While it is expected that most of Europa’s surface has been processed by irradiation from energetic electrons, it should be possible to find regions where very little radiation processing has occurred. These regions will be useful to study the composition of pristine surface ice and will be the best place to look for complex organics that cannot survive long on other parts of Europa.

References: [1] Johnson R. E. et al. (2009) *Europa,* 507-527. [2] Johnson R. E. et al. (2004) *Jupiter,* 485-512. [3] Carr M.H. (1998) *Nature 391.*

WATER PRODUCTION AND TRANSPORT IN THE ICE SHELL OF EUROPA. K. Kalousová[1,2], G. Tobie[2,3], O. Souček[4], G. Choblet[2,3], and O. Čadek[1], [1]Charles University in Prague, Faculty of Mathematics and Physics, Department of Geophysics, V Holešovičkách 2, 180 00, Praha 8, Czech Republic (kalous@karel.troja.mff.cuni.cz), [2]Université de Nantes, LPGNantes, UMR 6112, 2 rue de la Houssinière, F-44322, Nantes, France, [3]CNRS, LPGNantes, UMR 6112, 2 rue de la Houssinière, F-44322, Nantes, France, [4]Charles University in Prague, Faculty of Mathematics and Physics, Mathematical Institute, Sokolovská 83, 186 75, Praha 8, Czech Republic.

Tidal forces due to eccentric orbit around its parent planet play a significant role in the thermal-orbital evolution of Europa, the smallest Galilean satellite of Jupiter. The associated tidal deflection results in elevated heating, mostly located in the warm convective part of the ice shell and locally also along tectonic faults in the upper part of the ice shell, which might be strong enough to produce liquid water a few kilometers below the surface. The presence of large water lenses at shallow depths may possibly explain the formation of the so-called chaos terrains [1], observed in different locations on Europa's surface, or the ubiquitous double ridges [2].

Melting due to tidal heating at relatively shallow depths is expected either in the heads of hot plumes due to thermally-reduced viscosity [3],[4] or along tidally-activated strike-slip faults [5]. The localization of water production as well as the efficiency of its extraction is expected to depend strongly on the thermal structure of the ice shell. For temperature well below the melting point (cold ice), ice is essentially impermeable, e.g. [6], while in regions where temperature reaches the melting point (temperate ice), liquid water co-exists with ice and can be efficiently transported through the ice matrix. In partially molten areas, where heating rate is expected to be maximal [3], the water transport is controlled by the ice permeability and the deformation of ice matrix. In cold regions, water may be transported by the development of Rayleigh-Taylor instabilities and/or elastic hydrofracturing. The aim of this study is to determine the conditions under which a particular water transport mechanism may become dominant.

Partially molten areas are handled as a mixture of ice and water with both phases (solid and liquid) equipresent, and the two-phase flow formalism, e.g. [7], is used. Simulations performed in 1D geometry, as well as preliminary results in 2D geometry, show that water is transported downwards very efficiently in the form of successive porosity waves, with the ice permeability being the main control of the timescale of the process. The time needed to transport a substantial amount of liquid water from Europa's shallow subsurface to the underlying ocean varies between ~ 1 - 100 kyr. Consequently, water produced in the head of tidally-heated hot plumes probably never accumulates at shallow depths and is rapidly extracted from the ice shell.

Based on these simulations, the only places where a significant water fraction might temporarily accumulate are cold conductive regions subjected to strong tidal friction [8]. However, the accumulation of dense liquids above an impermeable cold ice layer may lead to the development of Rayleigh-Taylor instabilities and hence larger volumes of liquid water may be stable only if the underlying ice is cold enough. We are currently developping numerical models to determine the mechanical stability of such perched water lenses.

Another mechanism which could be dominant in this cold context is the discharge of subsurface water reservoirs by crevasse hydrofracturing, in analogy with rapid drainage of supraglacial lakes on the Earth [9]. However, limited crack initiation within the ice shell (due to overburden pressure), smaller heat generation rates and thicker ice layer than on the Earth imply that water discharge within the ice shell of Europa is probabbly different from that within the Earth's glaciers. In order to assess the efficiency of hydrofracturing on Europa, we are currently adapting elastic fracturing formalism [9] to Europa conditions. Preliminary results will be presented.

Acknowledgements: This research received funding from the European Research Council under the European Community's Seventh Framework Programme FP7/2007-2013 Grant Agreement no. 259285 and the project LL1202 in the programme ERC-CZ funded by the Ministry of Education, Youth and Sports of the Czech Republic.

References: [1] Schmidt, B. E. et al. (2011) *Nature, 479,* 502–505. [2] Dombard, A. J. et al. (2013) *Icarus, 223,* 74–81. [3] Tobie, G. et al. (2003) *JGR, 108,* 5124–5138. [4] Sotin, C. et al. (2002) *GRL, 29,* 1233–1236. [5] Nimmo, F. and E. Gaidos (2002) *JGR, 107,* 5021–5028. [6] Gusmeroli, A. et al. (2010) *JGR, 115*. [7] Bercovici, D. et al. (2001) *JGR, 106,* 8887–8906. [8] Kalousová, K. et al. (2013) submitted to *JGR*. [9] Krawczynski, M. J. et al. (2009) *GRL*, *36.*

SUBDUCTION ON EUROPA: A NUTRIENT CONVEYOR BELT INTO THE ICE SHELL?

S. A. Kattenhorn[1] and L. M. Prockter[2], [1]Department of Geological Sciences, University of Idaho, Moscow, ID 83844-3022, U.S.A., simkat@uidaho.edu, [2] Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, U.S.A., Louise.Prockter@jhuapl.edu.

Introduction: The 2003 Planetary Decadal Survey, "New Horizons in the Solar System," and 2011 Planetary Decadal Survey, "Vision and Voyages," both emphasize the importance of Europa exploration as "the first step in understanding the potential of the outer solar system as an abode for life" [1]. A tidally heated global ocean beneath its ice shell is important for astrobiological considerations; however, habitability requires a source of chemical nutrients. Europa's radiolytically processed surface is a potential source, but a means of delivery of compounds to the ocean is required. We describe a region in Europa's northern trailing hemisphere where large portions of the surface have been removed along discrete tectonic boundaries that we hypothesize to be subduction zones. These zones are commonly ~30 km wide and can be traced up to 1700 km across the surface in low-resolution imagery.

Subduction implies that the outer, brittle portion of the ice shell behaves in a similar way to Earth's lithospheric plates, with the warmer, deeper portions of the shell behaving like Earth's thermally convecting asthenosphere, into which the brittle portion can subduct. Just as plate tectonics on Earth was fundamental for creating a habitable environment, plate tectonics on Europa may have provided a means to recycle nutrient-rich chemical compounds from the surface into the Europan interior and thus contribute a potential energy source for astrobiological development.

Europa's Surface Age Paradox: Europa's surface has an abundance of extensional features (e.g., dilational bands) but scant evidence of contraction [e.g., 2, 3, 4]. Moreover, the crater-based surface age (40-90 Myr) [5] indicates one of the solar system's youngest surfaces, implying Europa's surface may have been recycled in this time frame. Subduction provides a mechanism to recycle surface materials and reset crater ages.

Tectonic Reconstruction: We have reconstructed geologic features in a 106,000 km^2 candidate region in Europa's northern trailing hemisphere, imaged at 170-228 m/pixel, to show that the current surface configuration involved numerous translations and rotations of rigid plates. The reconstruction reveals ~92 km of missing surface that seemingly vanished along a 23-km-wide, >300-km-long, band-like zone with unusual color characteristics. We refer to this and analogous bands as "subsumption bands" and hypothesize that they represent candidate subduction zones.

Numerous lines of evidence show that the geological history of the region involved mobile plates and surface removal, including a mismatch of older geological features across discrete boundaries, missing surface area in tectonic reconstructions, distinctive and unique surface morphologies at plate edges (both transform-like and subduction-like boundaries), a lack of topographic expression (implying area removal, not contractional strain within a narrow zone), cryovolcanic or thermal disruption features restricted to the overriding plate, spatially distinct color or albedo characteristics, and partitioning of strain along portions of plate boundaries that are obliquely convergent (transpressive).

Discussion: If a subduction model for Europa is accurate, buoyancy constraints and a lack of contractional topography imply that the subducting slab does not enter the ocean directly. We thus interpret a thin (~several km), brittle lid overlying a thicker, convecting ice layer, with plate motions and subduction restricted to the brittle lid. The subducting plate is presumably consumed at a rate conducive to complete subsumption into the convecting layer as it moves into the warmer portion of the ice shell. On Earth, oceanic lithosphere removal along a cumulative 55,000 km length of subduction zones occurred in <200 Myr at 20-80 mm/yr. Similar subduction rates on Europa (if valid) along only 30,000 km total length of subduction zones could recycle its surface area (~6% of Earth's) over a time frame consistent with its surface age.

Subduction provides a new paradigm for interpreting Europa's surface features and age, as well as a mechanism to deliver nutrients from the surface to either the ocean or pockets of liquid water within the ice shell [6]: crucial for astrobiology and habitability. If subduction exists, Europa is the only other solar system body beyond Earth to exhibit plate tectonics, involving subduction (surface area removal), mid-ocean-ridge-like spreading (surface area creation at dilational bands) [7], and transform motions.

References: [1] Space Studies Board (2003, 2011). [2] Greeley et al. (2000). *J. Geophys. Res., 105,* 22,559–22,578. [3] Kattenhorn and Hurford (2009) In: *Europa*, 199-236. [4] Sarid et al. (2002) *Icarus 158*, 24-41. [5] Bierhaus et al. (2009) In: *Europa*, 161–180. [6] Schmidt et al. (2011) *Nature* 479, 502-505. [7] Prockter et al. (2002) *J. Geophys. Res. 107*, 10.1029/2000JE001458.

COMPOSITIONAL MAPPING OF EUROPA'S SURFACE WITH A DUST MASS SPECTROMETER.

S. Kempf[1], N. Altobelli[2], C. Briois[3], T. Cassidy[1], E. Grün[1], M. Horányi[1], F. Postberg[4], J. Schmidt[5], S. Shasharina[6], R. Srama[4], and Z. Sternovsky[1] [1]LASP, CU Boulder, USA, [2]ESA, ESAC, Spain, [3]LPC2E, Orléans, France, [4]IRS, Universität Stuttgart, Germany, [6]University of Oulu, Finland, [6]Tech-X Corporation, Boulder, CO, USA

Introduction: We developed a dust mass spectrometer (SUrface Dust Analyser - SUDA) to measure the composition of ballistic dust particles populating the thin exosphere that was detected around Europa. Because these grains are samples from the moon's icy surface, unique information will be obtained about the grains' composition, constraining geological activities on and below the moon's surface. The instrument will contribute significantly to answer main scientific questions of NASA's Europa Clipper mission, in particular about the surface composition, habitability, the icy crust, and exchange processes with the deeper interior of Jovian icy moon Europa.

Dust Exoclouds: The basic idea of compositional mapping [1] [2] is that moons without an atmosphere are wrapped in clouds of dust particles ejected by meteoroid impacts from the moon's surfaces, whose composition can be analysed by and detected by an orbiter instrument. The ejecta production process is very efficient: a typical interplanetary 10^{-8} kg micrometeoroid impact on Europa produces a large number of dust particles with a total mass about 18 thousand times of the imp actor's mass [3]. The so-called ejecta particles move on ballistic trajectories and most of them recollide with the moon. As a consequence, an almost isotropic dust cloud forms around the moon [4] [5].

In 1999, the Galileo dust instrument measured the density profiles of the tenuous dust exospheres around each of the Galilean satellites [6]. The cloud density declines asymptotically with the distance as $r^{-5/2}$. This implies that a spacecraft in close orbits around Europa will be hit by a substantial number of eject arriving from apex direction with approximately spacecraft speed. The dynamic properties of the cloud particles are clearly distinct from any other kind of cosmic dust likely to be detected in the vicinity of the satellite.

Compositional Mapping: For every dust particle detected in the vicinity of the moon, the SUDA instrument is capable of constraining the location of origin on the surface. This enables the correlation of the measured dust composition to geologic features on the surface. This is accomplished by measuring the particles' velocity along the instrument axis to infer the most likely distance of the particle origin from the sub-spacecraft point with a possible resolution of a few tens of kilometers (Fig. 1). This allows simultaneous compositional mapping of many organic and inorganic components, including both major and trace compounds, with a single instrument.

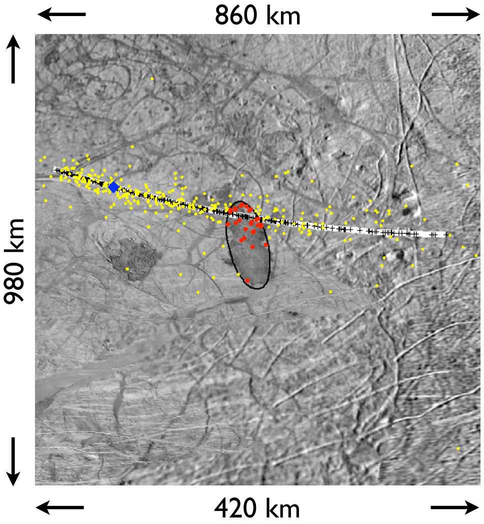


Fig. 1 The Monte Carlo simulation of ejecta dust particles shows that geological features (.e.g., Thrace Macula ,140 km in diameter, circled) can be mapped compositionally by SUDA. The indicated trajectory is Clipper's 25km E16 flyby.

Compositional Analysis: Measuring the composition of cosmic dust provides unique insight into the physical and chemical conditions at its origin as demonstrated recently by Cassini dust detector [7]. Information about the geological activities on and below a moon's surface, in particular about the material exchange between the interior and the surface, is contained in the types and amounts of organic and inorganic componets embedded in the dominant surface material. Relating composition to subsurface habitability requires knowledge of both the organic and inorganic inventory in surface materials. SUDA is uniquely capable of providing both and will detect a wide variety of compounds from the European surface over a concentration range of percent to ppm, and connect them to their origin on the surface.

References: [1] S. Kempf et al. (2009) *EPSC*, 472–473, [2] F. Postberg et al. (2011) *Planet. Space Sci.*, 371, [3] D. Koschny & E. Grün (2001) *Icarus*, 154, [4] A. V. Krivov et al. (2003) *Planet. Space Sci.* 51, [5] M. Sremcevic et al. (2003) *Planet. Space Sci.* 51, [6] H. Krüger et al. (1999) *Nature,* 399. [7] F. Postberg et al. (2009) *Nature*, 459.

CHARACTERIZING EUROPA'S SUBSURFACE WATER OCEAN FROM FUTURE ELECTROMAGNETIC INDUCTION STUDIES.

K. K. Khurana[1], V. Angelopoulos[1], M. G. Kivelson[1] and C. T. Russell[1], [1]Institute of Geophysics and Planetary Physics and Dept. of Earth and Space Sciences, Universtiy of California at Los Angeles, CA, 90095. Email: kkhurana@igpp.ucla.edu

Introduction: Magnetic field observations from the Galileo spacecraft obtained in the vicinity of Europa have shown that Europa produces a strong induction response to the rotating field of Jupiter's magnetosphere. The most plausible source of this induction response is a salty liquid ocean buried close to the surface of Europa [1, 2]. If a moon-wide ocean with a conductivity similar to the Earth's ocean exists on Europa, its thickness would have to be at least 6 km to be consistent with the observed induction signature.

Many other geological and geophysical observations are consistent with a deep global ocean [3] for further details.). The magnetic induction signature at a single frequency essentially determines the product of the conductivity and the thickness of the ocean. So a range of oceanic models is consistent with this interpretation. It has been further shown [4] that the current observations are consistent with a very salty ocean located in an ocean at a depth of no more than 50 kms. Because Galileo spends only short intervals in the vicinity of Europa during each flyby, induction signal at frequencies other than that corresponding to the synodic rotation period of Jupiter has not been determined.

Further Investigations: However, the spectrum of the primary field imposed on Europa by Jupiter does contain power at several other important frequencies. Among them, the frequency corresponding to the orbital period of Europa is particularly useful in inferring the depth, thickness and conductivity of the Europan ocean. We suggest that a key objective of future exploration strategies should be to characterize the electromagnetic induction at as many frequencies as possible so that the spatial extent and physical properties of the ocean can be fully explored.

Future Missions: We will discuss the needs and priorities for the spacecraft missions (orbital elements, duration, instrumental requirements etc.) and the surface observatories (number, configuration, duration etc.) in order to obtain an optimum dataset. We discuss how magnetometer measurements from future orbiting spacecraft or surface landers can be decomposed into the internal (which is the secondary field) and external (the primary imposed field) components not only for the steady field but also for the varying field. Finally, we will touch upon inversion techniques that can then be used to invert the observations and obtain information on the composition, structure and spatial distribution of the ocean.

References: [1] Khurana, K.K., M.G. Kivelson, D. J. Stevenson, and others (1998), Nature, 395, 777-780. [2] Kivelson, M.G., Khurana, K. K., D. J. Stevenson, L. Bennett. S. Joy, C.T. Russell, R. J. Walker, C. Zimmer and C. Polansky (1999), J. Geophys. Res., 104, 4609-4625. [3] Pappalardo, R.T., M.J.S. Belton, H.H. Breneman, and others (1999) J. Geophys. Res.,104, 24015-55. [4] Hand K. P. and Chyba, C.F. (2007), *Icarus 189*, 424–438.

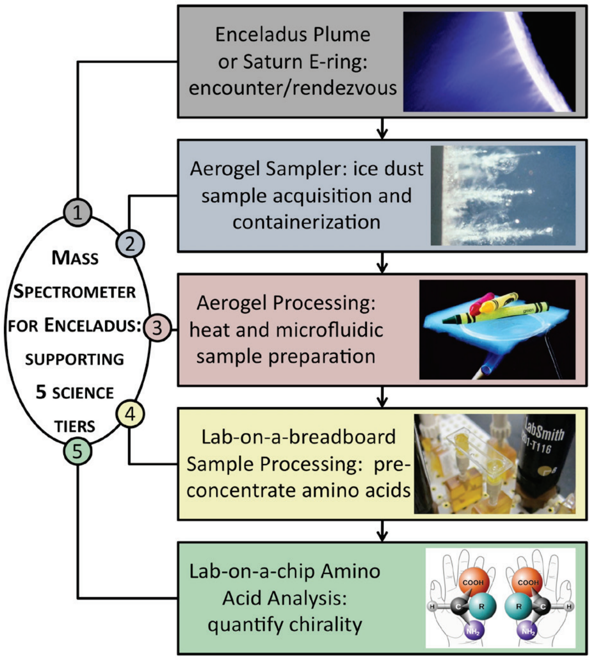
ENCELADUS REMOTE ORGANIC DETECTION: AEROGEL ICE PARTICLE COLLECTION AND IN SITU MASS SPECTROMETER ANALYSIS.

J. P. Kirby[1], S. M. Jones[2], P. A. Willis[2], M. S. Anderson[2], and A. G. Davies[2] [1]Planetary Science Institute (1700 E. Ft. Lowell, Suite 106, Tucson, AZ 28519, jpkirby@psi.edu), [2]NASA Jet Propulsion Laboratory.

Introduction: A new astrobiology science instrument concept is presented for a future mission to Enceladus [1]. Water ice particles and gas jets from the south polar regions of Enceladus form a massive plume that supplies material to Saturn and its E-ring [2, 3]. The Enceladus Amino Acid Sampler (EAAS) will address fundamental astrobiology science questions by providing detailed *in situ* chemical analysis of Enceladus jet and plume material [4]. The EAAS instrument concept enhances and expands the capabilities demonstrated by the Ion and Neutral Mass Spectrometer (INMS) instrument on the Cassini spacecraft [5, 6]. The INMS instrument has the capability to detect small amino acids, such as glycine and alanine [7]. However, INMS was not designed to collect hypervelocity ice particles in an aerogel matrix nor does the Cassini spacecraft have the capability to assess the chirality of amino acids for establishing biotic origin.

An aerogel matrix inlet to a mass spectrometer (MS) enables collection and analysis of hypervelocity ice dust particles in flight onboard a spacecraft [8], while mitigating sample alteration from dust impact with the instrument, as observed with the Cometary and Interstellar Dust Analyzer on the Stardust mission [9]. EAAS will enable the discovery of the identity, inventory *and* chirality of free amino acids. The composition of a habitable subsurface ocean, postulated to be present on Enceladus [10, 11, 12], could be determined with remote chemical analysis with EAAS, which is compatible with mission formulations for either an orbiter [1] or sample return spacecraft [13].

Enceladus Exploration EAAS Science Tiers: *1) Enceladus Encounter*. Hypervelocity encounter with the Enceladus plume or jets for real-time operation analogous to INMS provides ground truth measurements and calibration to INMS data [5, 6]; *2) Aerogel Sampler.* An aerogel matrix sampler inlet decelerates and entrains hypervelocity ice AND dust particles [13], liberating volatiles upon capture which are analyzed by the MS in near real-time; *3) Analysis of Volatiles Captured by Aerogel Chemisorption and Physisorption.* A sealable aerogel container allows for on-orbit, post-encounter heating or processing the aerogel with liquids or carrier gases, which are then fed to the MS for analysis; *4) Amino Acid Inventory Determination.* Sample pre-concentration with a lab-on-a-breadboard subsystem separates and pre-concentrates amino acids for MS analysis [14]; *5) Amino Acid Chirality Quantification.* Post-encounter lab-on-a-chip subsystems separate amino acids and quantify amino acid chirality, with MS detection for sample verification [15].



Acknowledgements: NASA's Astrobiology Program provided funding for this research.

References: [1] Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011) *The National Academies Press.* [2] Hansen C. J. et al. (2008) *Nature, 456,* 477-479. [3] C. J. Hansen, et al. (2006) *Science, 311,* 1422-1425. [4] Marais D. J. D. et al. (2008) *Astrobiology, 8,* 715-730. [5] Cravens T. E. et al. (2009) *Geophys. Res. Lett., 36*. [6] Matson et al. (2012) *Icarus, 221,* 53-62. [7] Hoerst S. M. et al. (2012) *Astrobiology, 12*, 809-817. [8] Elsila J. E. et al., (2009) *Meteorit. Planet. Sci., 44,* 1323-1330. [9] Kissel J. et al. (2004) *Science, 304,* 1774-1776. [10] Postberg F. et al. (2011) *Nature, 474,* 620-622. [11] Parkinson C. D. et al. (2008) *Origins Life Evol. B., 38,* 355-369. [12] Nimmo, F. et al. (2007) *Nature, 447*, 289-291. [13] Tsou P. et al. (2012) *Astrobiology, 12,* 730-742. [14] Mora M. F. et al. (2012) *Electrophoresis, 33,* 2624-2638. [15] Mora M. F. et al. (2011) *Anal. Chem., 83,* 8636-8641. [16] Cockell C. S. and Nixon S. (2013) Astrochemistry and Astrobiology, eds. Smith I. W. M. et al. Springer-Verlag Berlin Heidelberg, 211-241.

TOWARDS AN ASTROBIOLOGICAL VISION FOR THE OUTER SOLAR SYSTEM: THE EUROPA AND ENCELADUS EXPLORER MISSION DESIGNS.

K. Konstantinidis[1], C. L. Flores Martinez[2], M. Hildebrandt[3], and R. Förstner[1], [1]Bundeswehr University Munich, Institute for Space Technology and Space Applications, Werner-Heisenberg-Weg 39, 85579 Neubiberg, Bavaria, Germany, e-mail:k.konstantinidis@unibw.de [2]University of Heidelberg, Centre for Organismal Studies, Im Neuenheimer Feld 234, 69120 Heidelberg, Baden-Wurttemberg, Germany, e-mail: c.flores@stud.uni-heidelberg.de, [3]German Research Institute for Artificial Intelligence (DFKI), Robert-Hooke-Straße 5, 28359, Bremen, Germany, e-mail: marc.hildebrandt@dfki.de

Introduction: The firmly astrobiologically oriented exploration of the Solar System promises to revolutionize our understanding of how and where life in the Universe can originate, evolve and develop. In case organisms, which arose independently from terrestrial life, can be discovered beyond Earth, general notions of evolutionary biology, planetary science and even cosmology will undergo revision in light of more widespread biological activity throughout the Cosmos. In more practical terms the great hypothesis of a living Universe can only be verified, or falsified, via advanced robotic exploration and *in situ* sampling of putative alien biospheres. Since the highly successful Galileo and Cassini missions revolutionized our understanding of the outer Solar System, we can now be almost certain that more habitable regimes, than for example on Mars, have been identified within the subsurface environments of Jupiter's moon Europa and Saturn's Enceladus. Here, the process of emerging and evolving biological complexity is assumed to operate analogously among different putative planetary biospheres. This can be a helpful first assumption in guiding the design and construction of advanced robotic missions and adequate instrumentation that will aid in the eventual detection and characterization of biological activity on Europa and Enceladus.

The Potential for Life on the Icy Moons of Jupiter and Saturn: A comparative discussion of the astrobiological potential of the icy moons Europa and Enceladus, arguably the two prime targets across the outer Solar System, is given – in respect to the triad of parameters relevant to the concept of "life as we know it" (liquid water, biogenic elements and energy sources). Further, it is also considered how life could emerge within the subsurface environments of both moons from hydrogeological serpentinizing systems, subsequently evolve, and how differing degrees of biological complexity can be expected among the two kindred but far from identical planetary habitats.

Europa and Enceladus Explorer Mission Designs: Two DLR funded (National Aeronautics and Space Research Centre of the Federal Republic of Germany) mission concepts are presented:

Enceladus Explorer (EnEx) aims to design a mission to Enceladus, as well as to develop an operable drilling technique to penetrate the icy surface of the moon using the IceMole, a novel maneuverable subsurface ice melting probe for clean sampling and in-situ analysis of ice and subglacial liquids. The EnEx mission concept under development at the Institute for Space Technology and Space Applications (ISTA) of the Bundeswehr University Munich is comprised of a Lander carrying a nuclear reactor providing 5 kW of electrical power, and the IceMole, and an Orbiter with the main function to act as a communications relay between the Lander and Earth. After launch, the combined spacecraft uses the on-board nuclear reactor to power electric thrusters and eventually capture around Enceladus. The Orbiter then performs a detailed reconnaissance of the south polar terrain at Enceladus. At the end of the reconnaissance phase, the Lander separates from the Orbiter and autonomously lands near one of the active vapor plumes, where the IceMole is deployed and starts melting through the ice towards the target subglacial water bearing crevasse, adjacent to an active plume.

Europa Explorer's (EurEx) scope is the design of a fully integrated autonomous under-ice exploration system, which will be prototypically built by the DFKI (German Research Institute for Artificial Intelligence) and tested in arctic environments on earth in the course of 2013-2015. The focus in this project is the complete terrestrial demonstration of the feasibility of such an approach, especially the demands for navigation under the ice. The navigation system's role is critical for the mission: if the under-ice vehicle cannot return to its starting location (penetration point), no data can be transmitted back to earth, failing the complete mission. As a result the navigation system uses a combination of acoustic, optical and inertial localization techniques to ensure high-quality low-drop-out results.

Fusing Icy Moon Research Paths: Coupled with field work at terrestrial analogues of the icy moons (which is already taking place in the context of both projects with future expeditions already planned), such as, for instance, the (deep) sea below the Arctic and Antarctica, subglacial lakes and other ice-dominated environments, the cross-pollination between Europa and Enceladus mission requirements, designs, and usable prototype instrumentation could help in forging an interdisciplinary research program aimed at realizing the astrobiological vision for the outer Solar System.

EXPERIMENTAL FACILITIES TO SYNTHESIZE AND STUDY CLATHRATE HYDRATES: APPLICATIONS TO ICY MOONS.

E. Le Menn[1], D. Nna Mvondo[1], L.Bezacier[2], O. Bollengier[1], O. Grasset[1], G. Tobie[1], [1]Université de Nantes, CNRS, Laboratoire de Planétologie et Géodynamique, UMR-6112, 44322 Nantes, France, [2]European Synchrotron Radiation Facility, ESRF, 38000 Grenoble, France (erwan.lemenn@univ-nantes.fr)

Introduction: Gas clathrate hydrates probably play a key role in the storage and transport of gas compounds in water-rich environments, particularly in icy moons [1]. In order to understand how they may affect the chemical exchange processes in these icy objects, a series of experimental investigations have been carried out to constrain their phase diagram and to determine the infrared and Raman diagnostics. The complementary experimental facilities that has been developed at LPGNantes allow the controlled synthesis of mixed clathrate hydrate and their characterization over a wide range of temperatures, from 80 to 500K, and pressures, from 10^{-2} mbar up to 30 GPa. First results on mixture of methane-nitrogen and methane-carbon dioxide, compounds of high interest in planetology especially for the icy satellites of the outer solar system, will be presented.

Sample preparation apparatus:

We have developed two analytical facilities for the synthesis of mixed clathrates in controlled conditions.. The first set up consists of a gas mixer and a 100 ml vessel coupled to a gas chromatograph, and cooled by a Heto circulation chiller. This apparatus permits us to prepare relatively large volume of clathrate samples (~10 ml) and to measure the evolution of the gas phase during the clathration process. The synthesis can be performed for pressures ranging between 100 and 200 bar and for temperature down to 253 K.

The second one consists of a thin high pressure optical cell associated to a liquid nitrogen cryostat dedicated to infrared and Raman microanalysis under moderate pressures up to 200 bar. The principal interest of this apparatus is to synthesize a thin clathrate hydrate sample (150µm thick) into the cryostat and to allow the acquisition of infrared and Raman data without unloading the sample for the synthesis vessel. The cooling with liquid nitrogen allows a wider exploration of temperautre, down to 85 K.

Infrared spectroscopy in application to icy surface conditions:

The surface conditions of icy moons are reprocuded by the LN2 cryostat where the sample is maintained at low pressure and temperature conditions by PID controller. *In situ* near-IR and Raman spectra of the sample, crystal by crystal, are acquired using a Thermo Nicolet FTIR (Nicolet 5700) and a Horiba Raman spectrometer (LabRam 300) respectively. IR reflectance spectra of pure water icy and of CO_2 clathrate hydrate have been investigated [2][3] on the spectral range 1-5 µm. First results on the CH_4-N_2 clathrate hydrates will be presented (Nna Mvondo et al. 2013, AGU).

High pressure experiments: stability of clathrate hydrate within the icy mantles.

In order to determine the stability of gas clathrate hydrates over a wide range of pressure in application to the water-rich interiors. An experimental approach using Diamond and Sapphire Anvil Cells (DAC, SAC) coupled to a Raman spectrometer is carried out up to 10 GPa. The pressure is measured *in situ* by ruby fluorescence [4] and diamond sensors [5] in the case of the DAC and the SAC, respectively. This method was used to study the H_2O-CO_2 system up to 1.7 GPa [6] and the H_2O-CH_4 system up to 5 GPa [7], with applications for Ganymede and Titan. First experiments on CH_4-CO_2-H_2O binary clathrates have been performed and preliminary results will be presented.

Aknowledgements: The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013 Grant Agreement no. 259285) and from the University of Nantes, France.

References:

[1] Choukroun, M. et al., 2013: Gudipati, M., and Castillo-Rogez, J.C. (eds), The Science of Solar System Ices, 3rd edn. Springer.
[2] Taffin, C. et al. Planet. Space Sci. 61, 124-134, 2012.
[3] Oancea, A. et al. Icarus, Volume 221, Issue 2, Pages 900-910, 2012.
[4] Grasset, O. High Pressure Research, Vol 21, pp.139-157, 2001.
[5] Grasset, O. et al. High Pressure Research, Vol 25, pp.255-265, 2005.
[6] Bollengier, O. Geochimica et Cosmochimica Acta, Volume 119, Pages 322-339, 2013.
[7] Bezacier, L. submitted (Physics of the Earth and Planetary Interiors)

INVESTIGATING THE HABITABILITY OF CERES.

Jian-Yang Li[1], Mark V. Sykes[1], Asmin V. Pathare[1], J. P. Kirby[1], Julie C. Castillo-Rogez[2], [1]Planetary Science Institute, jyli@psi.edu, [2]California Institute of Technology, Jet Propulsion Laboratory.

Introduction: Ample evidence suggests that water must have played a significant role in the evolution of Ceres. Despite the nearly featureless spectrum of Ceres in the visible and near-infrared (NIR), the weak but mysterious absorption features in the 3-µm region have been variously interpreted as: water ice frost [1], NH_4-bearing phyllosilicate [2], mixture of irradiated organics and crystalline water ice [3], iron-rich clay and carbonates [4], and brucite ($Mg(OH)_2$) [5]. All of these possible compositions require an H_2O-based origin. The density of Ceres is consistent with ~25% water by mass [6]. The HST images [7] and ground-based NIR observations of Ceres [8, 9] show a remarkably homogeneous surface, a possible consequence of relatively recent or even current resurfacing driven by liquid-phase activity and/or volatile sublimation and mass transport [cf 10]. A marginal detection of OH off the northern limb of Ceres was reported [11], although subsequent searches returned negative results [12]. Thermal evolution modeling of Ceres [13, 14] suggests liquid water in the mantle in the past and perhaps even today. Water ice can remain in shallow subsurface at mid- to high-latitude areas on Ceres for the age of the solar system [15, 16].

The potentially large H_2O fraction in Ceres, existence of subsurface liquid water, and active exchange of materials between the surface and subsurface make Ceres an intriguing target for astrobiology. With its much closer proximity to the Earth compared to icy moons, and lower surface gravity relative to Mars and large moons, Ceres could be a prime target for future space missions to study the habitability on or beneath the surface of an ice-rich body.

NASA's Dawn spacecraft will arrive at Ceres in April 2015 for a nominal 5-month mapping rendezvous [17]. With the prospect of obtaining high-resolution maps of Ceres' geology, mineralogy, elemental abundance, and gravity by Dawn, we expect that our understanding of Ceres will be greatly advanced.

Perspectives: The astrobiological potential of Ceres needs to be better understood with a systematic, coordinated study combining observational and theoretical approaches. We envision that this investigation would have several key components: long-term, high-resolution monitoring of the surface of Ceres for its spectral reflectance; continued searches of active water sublimation on Ceres covering a full orbital period; and thermal mapping. These long time-baseline campaigns would be a critical complement to Dawn's detailed portrait of Ceres. Essential for these observations are high-resolution and/or high signal-to-noise. Of particular interest, thermal mapping in the sub-mm wavelengths is an especially powerful technique for directly probing the subsurface thermal properties at or beneath the diurnal thermal skin depth (~1 mm). Ceres shows much larger (~50%) rotational variations in sub-mm flux [18], in contrast to the ~4% variations in visible light, indicating highly heterogeneous subsurface layers that could reflect variations in the relative fractions of water ice mixed in the regolith. The prospect that water ice would be accessible a few centimeters below Ceres' surface is exciting. Further observations, over extended timescales, are necessary to confirm and better interpret the Chamberlain et al. conclusions [18]. The ALMA Observatory would be the best facility to provide the desired angular resolution and would complement the bistatic scattering radar observations to be performed by Dawn.

Input as constraints to theoretical modeling, these new observations would lead to a better understanding of the depth and state of subsurface water ice. In addition to physical observation and modeling, complementary insights about the chemical environment of Ceres' surface and subsurface would be gained from compositional mapping. All in all, such an interdisciplinary investigation would greatly benefit the assessment of Ceres' past and present habitability.

References: [1] Lebofsky, L.A. et al. (1981) *Icarus 48*, 453-459. [2] King, T.V. et al. (1992) *Science 255*, 1551-1553. [3] Vernazza, P. et al. (2005) *A&A 436*, 1113-1121. [4] Rivkin, A.S. et al. (2006) *Icarus 185*, 563-567. [5] Milliken, R.E., Rivkin, A.S. (2009) *Nat. Geosci. 2*, 258-261. [6] Thomas, P.C., et al. (2005) *Nature 437*, 224-226. [7] Li, J.-Y., et al. (2006) *Icarus 182*, 143-160. [8] Carry, B., et al. (2008) *A&A 478*, 235-244. [9] Carry, B., et al. (2012) *Icarus 217*, 20-26. [10] Rivkin, A.S., et al. (211) *Space Sci. Rev. 163*, 95-116. [11] A'Hearn, M.F., Feldman, P.D. (1992) *Icarus 98*, 54-60. [12] Rousselot, P. et al. (2011) *AJ 142*, 125 (6pp). [13] McCord, T.B., Sotin, C. (2005) *JGR 110*, E05009. [14] Castillo-Rogez, J.C., McCord, T.B. (2010) *Icarus 205*, 443-459. [15] Schorghofer, N. (2008) *ApJ 682*, 697-705. [16] Prialnik, D., Rosenberg, E.D. (2009) *MNRAS 399*, 79-83. [17] Russell, C.T., et al. (2011) *Space Sci. Rev. 163*, 3-23. [18] Chamberlain, M.A., et al. (2009) *Icarus 203*, 487-501.

THE ASTROBIOLOGY OF TITAN. J.I. Lunine, Center for Radiophysics and Space Research, Cornell University, 402 Space Sciences Bldg., Ithaca NY 14853, jlunine@astro.cornell.edu.

Introduction: Titan is the only solar system world outside of the Earth which has an active volatile cycle involving stable surface liquids. The primary component existing in gaseous, liquid and possibly solid form is methane; secondarily ethane (a product of methane photolysis high in the atmosphere) participates as well. The background atmospheric gas is molecular nitrogen, with a surface temperature of 94 K(equatorial) and pressure of nearly 1.5 bars.

The equivalent of the terrestrial hydrologic cycle on Earth is the methane cycle on Titan [1]. The dropping temperature with altitude allows methane to condense out as clouds at altitudes of 8 km (equatorial) and above; precipitation of methane rain, with an admixture of nitrogen and possibly ethane, occurs in particular latitudes according to season, with some evidently intense storms scouring the surface [2]. Unlike Earth's hydrologic cycle, in which very little water escapes to the photolytically active stratosphere and mesosphere, the temperature of Titan's tropopause is such that large amounts of methane end up in the stratosphere and above, where conversion (with nitrogen and a little oxygen) to hydrocarbons, nitriles, and carbon (mon+di)oxide occurs. Hydrogen is lost to space and the products rain out on the surface as solids and (for ethane, propane and butene) liquids. Ample evidence for both exists in the equatorial dunes made of organic particles, and the polar lakes and seas.

The density of Titan, along with the near-identity of bulk properties with Jupiter's Ganymede and Callisto, strongly imply an interior made of nearly equal parts water and silicate (presumably with metals). Some of the silicate may be hydrated, while strong evidence for a liquid water layer exists primarily in gravity data of Titan [3]. Given this, the extent of the ice layers in Titan may be more limited than previously thought from Voyager data. Indeed, it is possible for the water ocean to be in contact with underlying rock.

Environments of Astrobiological Interest: Three environments on Titan are likely to be of interesting in either hosting life or preserving evidence of chemical processes leading to life. Deepest is the liquid water ocean, which likely has large amounts of organics and possibly dissolved salts from leaching associated with early hydration. In the crust itself, sites of impacts or cryovolcanism may remain melted for centuries of millennia, protected by a cap of insulating ice. Within these sites, organic molecules reacting with water may undergo self-organization to an extent limited by time and energy. Once refrozen, these sites may preserve the results of such prebiotic experiments for study.

Most interesting is the third environment, the polar lakes and seas, which are almost certainly mostly ethane and methane. The extent to which nonaqueous liquids may be the solvent for an exotic biochemistry has been extensively treated elsewhere [4], but Titan provides a test of such ideas. Is life, of whatever basic biochemical variety, a natural outcome of the existence of organic molecules, abundant free energy, and surfaces with catalysts? Or is it a phenomenon peculiar to water? The detection of complex polymers associated with Titan's surface lakes and seas, as evidence of chemical self-organization on the way to (or across the threshold of) a nonaqueous form of life, would answer this question.

Analysis of multiple Cassini data sets [5] suggests an unexpected and puzzling sink of hydrogen at the surface of Titan. While a biological explanation must not be seriously contemplated until abiotic physical-chemical hypotheses are evaluated and (possibly) falsified, this problem illustrates the seductively complex nature of Titan's surface-atmosphere system.

Future exploration: Operation of the Cassini Saturn Orbiter until solstice in 2017 is essential to understanding how the northern seas interact with the climate during the time of maximum insolation, as well as to provide further opportunities to map the surface and probe the composition of seas, sands and skies. Beyond Cassini, the next mission arguably ought to be a lander to explore *in situ* the surface organic chemistry to understand the extent to which it has evolved beyond the products of atmospheric charged particle and ultraviolet chemistry. Alternatively, a balloon or specially-equipped orbiter would be capable of mapping terrains whose geological provenance is poorly understood thanks to the limited spatial and spectral resolution of the Cassini remote sensing investigations.

References:

[1] Lunine J. I. and Atreya S.K. (2008) *Nature Geoscience, 1,* 159-164. [2] Turtle E. P. et al. (2011) *Science, 331,* 1414-1417. [3] Iess L. et al. (2012) *Science,* 457-459. [4] Benner S.A. et al. (2004) *Curr. Opinion Chem. Biol., 8, 672-689.* [5] Strobel D.F. (2010) *Icarus, 208,* 878-886.

COMPOSITION AND DYNAMICS OF TITAN'S LAKES.

A. Luspay-Kuti[1], V. F. Chevrier[1], S. Singh[1], A. Wagner[1], E. G. Rivera-Valentin[2] and F. Wasiak [1]Arkansas Center for Space and Planetary Sciences, University of Arkansas (202 FELD U of A, Fayetteville, AR 72701. aluspayk@uark.edu), [2]Brown University (324 Brook St. Box 1846, Providence, RI 02912).

Introduction: The Cassini-Huygens mission led to the identification of hundreds of hydrocarbon lakes on the surface of Titan. These lakes are mainly confined to the colder and presumably more humid polar regions, with more observed lakes in the north [1]. While inferred to be composed of substantial amounts of methane and ethane [e.g. 2], the concentration and stability/dynamics of these hydrocarbons in the lakes are poorly constrained. Here we report experimental simulations of the evaporation of liquid methane, ethane and mixtures thereof, obtained at a temperature and pressure relevant to Titan's poles (92 K and 1.5 bar N_2) for various methane-ethane compositions. Furthermore, we use the results to estimate the ethane content of the southern polar lake Ontario Lacus.

Methods: The facility used for the experiments was specifically designed for simulating Titan surface conditions [3]. When Titan-appropriate temperature and pressure conditions are reached, we condense the desired hydrocarbon(s) into a petri dish inside the simulation chamber. Using gas injection times and fluxes we control the liquid masses of these hydrocarbons based on the desired concentrations to be simulated. We determine the evaporation rate by a least-squares fit to various portions of the data depending on the simulated sample.

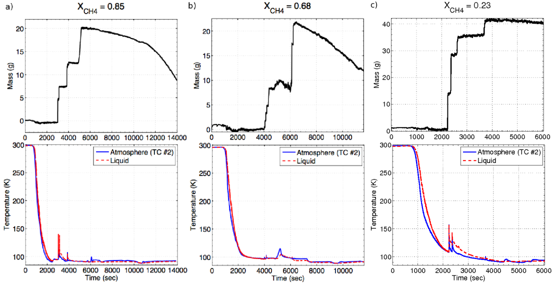


Figure 1. Mass vs. time (top) and temperature vs. time (bottom) curves for CH_4-C_2H_6 mixtures with different concentrations.

Results: After correcting for the gravity difference between Earth and Titan, we determine an average evaporation rate of $(1.6\pm0.3)\times10^{-4}$ kg m^{-2} s^{-1} of pure CH_4 [4]. Evaporation is negligible for pure C_2H_6 at the scale of our experiments. Evaporation rates for mixtures with various CH_4-C_2H_6 compositions are shown in Figure 2.

Model for Binary Mixture Evaporation: To understand the underlying evaporation processes we have developed a model based on mass loss through diffusion and buoyancy. The model used for pure CH_4 evaporation [4] has been adapted and modified for binary mixtures. Results from the model for dry and humid atmospheres are also shown in Figure 2.

Discussion: We show that the lack of pure C_2H_6 evaporation is due to its extremely low saturation pressure combined with the fact that it is not buoyant in a N_2 atmosphere. Mixture evaporation, however, increases nearly linearly with increasing CH_4 concentration, although at a lower rate than would be expected for a simple binary mixture. Indeed, methane is the only volatile phase, but early dissolution of N_2 in methane-rich environments results in a ternary mixture that further reducing evaporation**.** As our experiments show, this initial N_2 dissolution is only prominent for mixtures with CH_4 concentrations > 70 mol%.

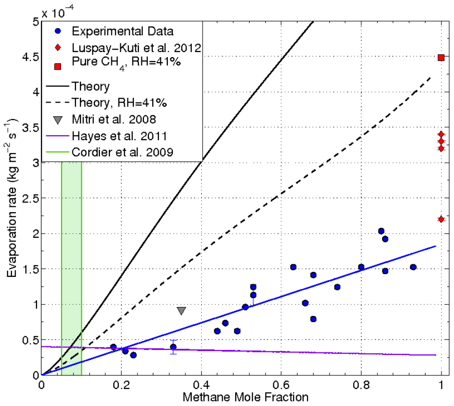


Figure 2. Evaporation rate as a function of methane mole fraction. Evaporation rate results from previous models and observation are also shown.

Implications for Titan: From our experimentally determined evaporation rate and the observed shoreline changes of Ontario Lacus [5] we approximate the methane content of Ontario Lacus to be 10-20%. This implies that it is primarily composed of ethane, hence it is most probably a residual lake that has incurred extensive methane evaporation.

References: [1] Aharonson O. et al (2009) *Nature Geosci. 2,* 851-854. [2] Cordier et al. (2009) *ApJL 707,* L128-131. [3] Wasiak et al. (2013) *ASR 51,* 1213-1220. [4] Luspay-Kuti et al. (2012) *GRL 39,* L23203. [5] Hayes et al. (2011) *Icarus 211,* 655-671.

Acknowledgements: This work was funded by the NASA Outer Planet Research Program #NNX10AE10G.

TRANSPORT AND CONCENTRATION OF ORGANIC MOLECULES ON TITAN-LIKE WORLDS.

Michael J. Malaska, Robert Hodyss, Morgan L. Cable,[1] Mathieu Choukroun[1], Tuan Vu[1], Jason W. Barnes[2], Shannon MacKenzie[2]. [1]Jet Propulsion Laboratory / California Institute of Technology, Pasadena, CA. [2]University of Idaho, Moscow, ID. (Michael.J.Malaska@jpl.nasa.gov).

Introduction: Titan represents a class of icy worlds where organic chemistry reigns supreme [1]. Understanding how complex organic molecules are moved and concentrated on planetary surfaces will quantify the potential for feedstock deposition and perhaps even the chemical processes before the initiation of life itself. In our Solar System, Titan represents a frozen laboratory where prebiotic chemical processes can be examined.

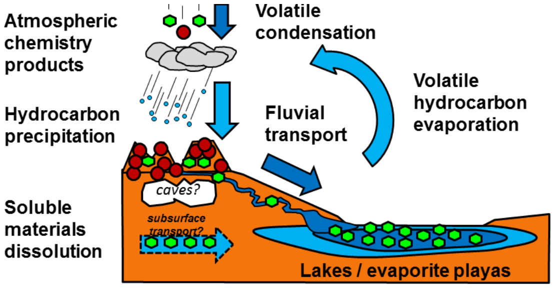


Figure. 1. Hydrocarbon fluid cycle on aTitan-like world.

Titan Hydrocarbon Cycle: On Titan, high-altitude photochemistry creates complex organic molecules that eventually deposit on the surface.[2, 3] Many of these molecules represent the earliest precursors and starting materials for prebiotic synthesis. The deposits are subjected to hydrocarbon rains that occur as part of a volatile cycle similar to the terrestrial water cycle (Figure 1). On exposure to the cycling fluids, soluble organic molecules are dissolved, transported, emplaced, and concentrated. The goal of our laboratory experiments is to understand these processes on Titan-like worlds.

Dissolution: We experimentally determined equilibrium solubilities and the kinetics of dissolution for benzene, naphthalene, and biphenyl in ethane at 94 K.[4] We found that dissolution is relatively rapid, even at cryogenic temperatures. The speed of dissolution is comparable to salts such as gypsum that are commonly leached out of terrestrial deposits.[5]

Transport: Once in solution, the fluids are carried by the numerous rivers and channels that have been described on Titan's surface[6] and possible subsurface conduits.[7] The dissolved materials follow fluid paths down local and regional topography to collect in local basins and depressions.

Concentration and Emplacement: As the solvent volume is reduced via evaporation, the dissolved solids will reach their saturation points and precipitates out of solution to build up a layer of organic material in the bottom of the lakes and playa basins.[8] Complete drying creates a remnant evaporite deposit of concentrated organic materials.[9] Several transport/drying cycles on seasonal or epochal scales could build up a multi-layer stack of deposited organics. A model assuming an average rate of 1 cm pure ethane precipitation over 1 year (terrestrial) moving a non-limiting supply of aromatics with a 10:1 drainage:lake area ratio, gave 2.2 microns of accumulated aromatic deposit. A similar model including the theoretical solubility of HCN resulted in a yearly deposit thickness of 1.6 mm.

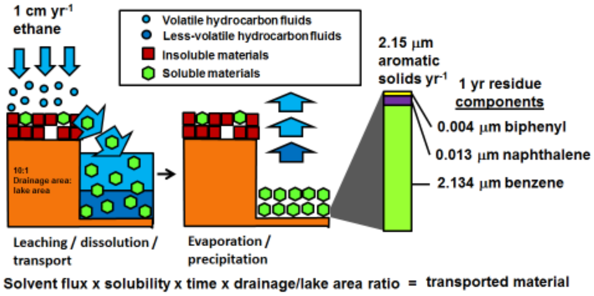


Figure 2. Model showing amount of yearly transport of benzene, naphthalene, and biphenyl in ethane fluid at 94 K..

Conclusions: Our laboratory measurements of equilibrium solubilities and evaporite structures, when combined with atmospheric flux rates, precipitation rates, equilibrium solubilities, drainage areas, and evaporation rates, can help determine how organic materials are moved and concentrated on a Titan-like planetary surface.

Acknowlegements: Support from the NASA Postdoctoral Program, NASA Astrobiology Institute (Titan), ASTID, and Outer Planet Research (OPR) programs is gratefully acknowledged.

References::[1] Lorenz et al. (2008) *GRL*, *35*, L2206. [2] Krasnopolsky, V.A. (2009) Icarus . 201, 226-256. [3] Lavvas et al. (2008) *PSS*, *56*, 67-99. [4] Malaska and Hodyss, (2013) *LPSC 44*, Abstract 2744. [5] Jeschke et al. (2001) *Geochimica et Cosmochim Acta 65*, 27-34. [6] Burr et al. (2013) *GSA Bulletin 125*, 299-321. [7] Mitchell et al. (2008) *LPSC 39* Abstract 2170. [8] Cordier et al. (2009) *Astrophysical J.* 707 L128-L131. [9] Barnes et al. (201) *Icarus*, *216*, 136-140.

HABITABILITY AND COMPOSITION AT EUROPA.

William B. McKinnon[1], J. H. Waite, Jr.[2], T. Brockwell[2], M. McGrath[3], D. Wyrick[2], and O. Mousis[4] ([1]Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis, MO 63130, mckinnon@wustl.edu; [2]Southwest Research Institute, San Antonio, TX and Boulder, CO; [3]NASA Marshall Space Flight Center, Huntsville, AL;; and [4] CNRS Observatoire de Besancon, Besancon, France)

Introduction: Whether Europa is habitable or not, and even if it is, the question of whether it would be (or is) a robust or moribund habitat depends in large measure on the composition of its surface, ice shell, subsurface ocean and rocky mantle. Compositional issues are comprehensively discussed in [1,2] and related to habitability in detail in [3,4]. This paper further addresses some of the relevant issues. It takes the point-of-view that a comprehensive and precise orbital survey of Europa's surface composition is of as great a value in terms of astrobiology as a suitably equipped lander, although obviously the very best course would be to include both, which would provide ground truth and calibration whilst offering the chance to discover the unexpected. For example, consider the following.

Oxidation State of the Ocean: As has been extensively discussed in the literature, the oxidation state in the ocean and the subjacent rocks clearly play a major role in Europa's habitability. The only thing we know for sure is that the very surface of Europa is oxidizing, due to radiolysis caused by intense jovian magnetospheric ion and electron bombardment [5]. The existence of possible redox couples determines the nature and productivity of potential subsurface life, but we do not know the oxidation state of what lies beneath. If material can get from the surface to the ocean (which is surely true in some sense and over some time scales), then the ocean will slowly oxidize (indeed as our own ocean did at the end of the Archean).

Transport mechanisms include impact breaches of the ice shell (e.g., Tyre), putative melt-throughs (if that is what some chaos features actually are), and whatever tectonically consumptive process balances crustal spreading and band formation on Europa [6]. On the other hand, hydrothermal activity can exert a countervailing redox control. Igneous systems on Earth (both mafic and felsic) tend to impose, through mineral buffering, more reduced oxidation states. Extensive hydrothermal activity is quite plausible early in Europa's history due to radiogenic heating alone. The degree of activity today is far less certain. What appears to be true is that tidal heating can partition predominantly in the ice shell [7], but that if the thermal conditions are just right (meaning hot and near-solidus), then strong tidal heating can occur in the rock mantle as well [8]. A prerequisite for this condition may be a higher orbital eccentricity than Europa exhibits today. Such eccentricity variations are expected over 10s to 100s of millions of years [8].

Sulfur Chemistry and Composition: The oxidation state of the interior will manifest itself through those elements with multiple valence states (e.g., C, S, Fe). Sulfur is particularly intriguing because it exists on the surface of Europa as a hydrated sulfate [1] and participates in a radiolytic sulfate cycle [5]. But does this sulfate come from the ocean as many suspect, or is it a radiolytic product? Zolotov and Kargel [2] argue on solubility grounds that its is more likely to be sulfate, because the solubility of reduced sulfur (HS) is so low. On the other hand, the sulfur may be exogenic (from Io), as Brown and Hand [9] argue, which points toward a sufidic rather than a sulfate-rich ocean.

It is quite plausible that Europa started with a sulfidic ocean, due to the oxidation of iron metal and sulfide and hydroxylation of Fe-bearing mafic and ultramafic silicates to produce (e.g.) magnetite and brucite [e.g., 10]. But loss of released hydrogen to space could move the ocean, and rocks that interact with it, in a more oxidized direction. This is actually a good thing from the point of view of habitability, because too much oxidant early on is not the appropriate condition for formation of important biological molecules such as purines and pyrimidines, which are steps organic matter takes to be self-replicating.

It is likely that the sulfur belched from Io's global volcanic system, and mixed into the torus, has a different isotopic signature from the sulfur sweated out of Europa's ancient or extant hydrothermal systems. Isotopic measurements from the Europa Clipper could tell the two sources apart, and with measurement of other redox sensitive components, determine the oxidation state of Europa's ocean.

References: [1] Carlson R. W. et al. (2009) in *Europa*, Univ. Ariz. Press, 283–387. [2] Zolotov M. Yu and Kargel J.S. (2009) in *Europa*, Univ. Ariz. Press, 431–457. [3] Hand K.P. et al. (2009) in *Europa*, Univ. Ariz. Press, 589–629. [4] Pappalardo R.P. et al. (2013) *Astrobiol., 13*, 740–773. [5] Johnson R.E. et al. (2009) in *Europa*, Univ. Ariz. Press, 507–527. [6] Kattenhorn S.A. and Hurford T. (2009) in *Europa*, Univ. Ariz. Press, 199–236. [7] Sotin C. et al. (2009) in *Europa*, Univ. Ariz. Press, 85–117. [8] Moore W.B. and Hussmann H. (2009) in *Europa*, Univ. Ariz. Press, 369–380. [9] Brown M.E. and Hand K.P. (2013) *Astron. J., 145:110*, 1-7. [10] McKinnon W.B. and Zolensky M.E. (2003) *Astrobiol.*, *3*, 879–897.

LIVING ON THE EDGE: THE HABITABILITY OF TRITON AND OTHER LARGE KUIPER BELT OBJECTS.

William B. McKinnon, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis, MO 63130, 341-966-3989 (mckinnon@wustl.edu).

Introduction: The Kuiper belt comprises a vast reservoir of bodies whose most direct interaction with inhabited (Earth) and potentially inhabited (Mars, Europa, Enceladus) worlds is through impact of short-period, or JFC, comets. Such impacts can deliver water as well as biologically essential elements (CHONPS, etc.) to otherwise barren bodies. The focus here, however, is on the Kuiper belt objects (KBOs) themselves, and in particular, the potential habitability of the largest, dwarf planet members of this class. I will emphasize Triton, as the largest "KBO" and the one with the most vigorous geological history (an aspect of critical importance). While such a discussion is necessarily speculative, it allows consideration of what we know or think we know about habitability in general, and may help clarify issues and indicate where to best place our exploration efforts.

Living on the Edge … of the Solar System: Any discussion of habitability must begin with the big three major requirements for life as we know it [e.g., 1]: 1) water; 2) biologically essential elements; and 3) a source of energy. At condensation temperatures in the outer Solar System, an abundance of water ice is a foregone conclusion. All large KBOs are known to be icy from surface spectra alone, if not bulk density. But icy surfaces mask rock-rich interiors. All of the dwarf-planet-class bodies (Pluto, Eris, Triton, Haumea…even Ceres) have densities of ≈ 2000 kg m^{-3} or greater, implying rock/ice ratios >1 (only Makemake's density is unknown) [2]. Detections of methane, ethane, and methanol on various KBO surfaces and the inferred presence of tholins (accounting for redness) imply an organic component as well, and if comets are any guide, this organic component is substantial.

Extensive studies (of meteorites, asteroids, comets, etc.) imply that Triton and other KBOs accreted more-or-less equal amounts of ices (including volatile organics), less volatile carbonaceous matter (CHON), and refractory "rock" (see references in [2]). Volatile ice compositions are best represented by cometary comae [e.g., 3], while the rock component may resemble the most primitive carbonaceous chondrites [e.g., 4]: essentially solar in composition (with respect to non-volatile elements) but only partially, aqueously altered. All biologically essential elements are thus included.

Triton: It is widely accepted that Triton is a captured KBO [5], and the leading mechanism at present is binary exchange capture [6]. Numerical calculations that attempt to simulate capture in the context of the Nice model [e.g., 7] generally fail (the system is too dynamically hot), so capture is relegated to earlier pre-LHB eras, or is simply taken to be an unlikely event [e.g., 8]. Late capture is ruled out because circularization would have destabilized Neptune's irregular satellites [8,9]. I note that collisional capture early in the Nice rearrangement may be just as likely, which makes Triton's formation distance from the Sun rather uncertain. Regardless of these details, Triton's post-capture tidal evolution was likely one of profound internal heating and thermochemical processing [5,10].

Habitability: Full differentiation of Triton and vigorous hydrothermal activity at the base of a deep (~350 MPa) ocean likely followed Triton's capture, even if its orbit partly circularized while cannibalizing Neptune's (putative) original satellite system [5,9]. This hyperactive era would have persisted for 100 m.y. and potentially much longer. Substantial conversion of accreted NH_3 to N_2 would have occurred for rock oxidation states similar to the Earth's midocean ridges, but as long as oxidation state remained sufficiently reducing, copious quantities of simple organics (carboxylic acids, alcohols) could have been synthesized as well (adding to the original endowment of organics). H_2 production (from hydroxylation of silicates) would have been substantial, affecting the redox evolution of the high-pressure ocean and Titan-like atmosphere above [11]. Notably, reduced P could have released into the ocean by reactions with accreted $(Fe,Ni)_3P$. The ultimate concentration of NH_3 and CH_3OH determines whether the ocean stays in contact and interacts with the rocky mantle, or whether contact is lost and the ocean is isolated between ice I above and denser ice below. The atmosphere protects the surface from Neptune's magnetosphere particles, but ionizing cosmic rays can still produce surface oxidants, and the surface *is* in communication with the deeper ice shell.

References: [1] Hand K.P. et al. (2009) in *Europa*, Univ. Ariz. Press, 589–629. [2] McKinnon W.B. et al. (2007) in *The Solar System Beyond Neptune*, Univ. Ariz. Press, 213–241. [3] Mumma M.J. and Charnley S.B. (2011) *ARAA, 49,* 471–524. [4] Zolensky M.E. et al. (2002) *MAPS, 37*, 737-761. [5] McKinnon W.B. et al. (1995) in *Neptune and Triton*, Univ. Ariz. Press, 807–877. [6] Agnor C.B and Hamilton D.P. (2009) *Nature, 192,* 192–194. [7] Levison H.F. et al. (2008) *Icarus, 196*, 258-273. [8] Nogueira E. et al. (2011) *Icarus, 214*, 113–130. [9] Cuk M.C. and Gladman B.R. (2005) *Astrophys. J. Lett., 626*, L113–L116. [10] Shock E.L. and McKinnon W.B. (1993) *Icarus, 106*, 464-477. [11] Lunine J.I. and Nolan M.C. (1992) *Icarus, 100*, 221–234.

PRIDE – Passive Radio Ice Depth Experiment - An Instrument to Measure Outer Planet Lunar Ice Depths from Orbit using Neutrinos.

T. Miller[1], S. Kleinfelder[2], S. Barwick[2], D. Besson[3], A. Connolly[4], G.W. Patterson[1], A. Romero-Wolf[5], R. Schaefer[1], and H.B. Sequeira[1], [1]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd, Laurel, MD 20723, [2]University of California, Irvine, CA 92697-2625, [3]University of Kansas, Lawrence, KS 66045, [4]The Ohio State University, 191 W. Woodruff Ave., Columbus, OH 43210, [5]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Ms 67-204, Pasadena, CA 91109

Introduction: Indirect measurements by the Galileo and Cassini spacecraft indicate that substantial liquid water oceans are likely present beneath the outer icy shells of a number of moons orbiting Jupiter and Saturn. The conditions necessary to create and sustain such oceans have important implications for the astrobiological potential of those moons and therefore high priority has been given to their continued exploration. However, determining the thickness of the outer icy shells of these bodies has proven challenging, especially given available/proposed spacecraft resources. The current approach to addressing this question for ice shells such as Europa's (e.g., as conceived for the ESA JUICE mission and the NASA Europa Clipper concept) uses a suite of instruments (laser altimetry, magnetometer, and ice penetrating radar) to provide minimum/maximum constraints on ice shell thickness. Here, we describe a concept for a single instrument to measure the thickness of an ice shell, such as Europa's, by making use of the Askaryan Effect Radio Frequency signal from ultra high energy neutrinos.

Background: In the world of astrophysics, difficult problems can occasionally benefit from the use of results derived from seemingly unrelated areas. Determining the depth to, and thickness of, potential subsurface oceans on icy worlds is one of those problems, and here we explore how that problem benefits from work done in the world of high energy cosmic rays. The basic idea, illustrated in Figure 1, is to use radio receiver technology to detect cosmic ray neutrinos passing through the ice and generating Cerenkov radio pulses. EHE (> 10^{18} eV) cosmic ray neutrinos are produced from the interaction of cosmic ray protons with cosmic background radiation [1]. They can penetrate deep into ice and interact with nuclei to produce a particle shower. The moving particle shower produces Cerenkov radiation with a spectrum that peaks at ~0.2 to 2 GHz and it can be detected from orbit through radio transparent media (e.g., [3]). At typical Europan temperatures of ~100K, pure ice has attenuation lengths of tens of km or more. The thickness of an ice shell can then be determined from the rate, direction and magnitude of the received signals.

Concept: The PRIDE instrument concept is an array of small, low mass passive RF receivers that are read out by low-power, high speed digitizers (Switched Capacitor Arrays [4]). Simulations of ??? indicate ice shells up to tens of km thick are detectable (Figure 2). Work is currently being done to optimize components and configurations for the antenna, receiver, and electronics, and to further characterize the signal-to-noise environment. Additional options to further reduce mass and power are also being studied.

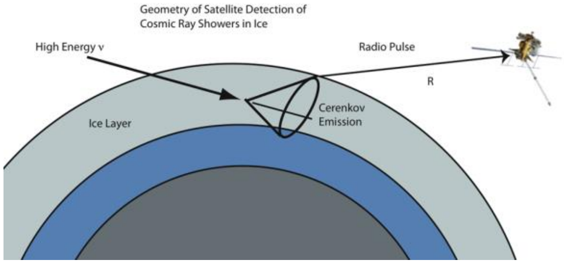


Figure 1. Illustration of the PRIDE concept. A high energy cosmic ray neutrino penetrates the ice at a grazing angle and initiates a shower of secondary charged particles that emit a detectable conical pulse of Cerenkov radiation. The distributions of the characteristics of detected pulses indicate the thickness of the ice layer.

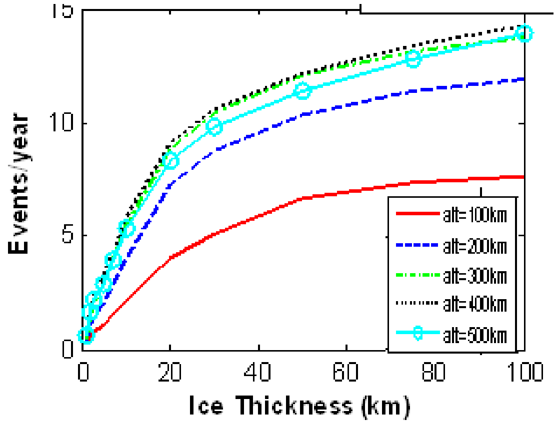


Figure 2. Events/year detected vs. ice sheet depth and satellite altitude, assuming a standard normalized E^{-2} spectrum. Depths up to tens of km can be measured if the incident neutrino flux is known.

References: [1] Waxman, E. and Bahcall, J.N., (1998) Phys.Rev. D59, 023002; [2] Miller, T., Schaefer, R.K., and Sequeira, H.B., *Icarus, 220, 877-888*, 2012. [3] Barwick, S. W., 30 colleagues, Phys. Rev. Lett., 96, 171101, 2006. [4] Kleinfelder, Proc SPIE 4858, 316-326, 2003.

PROGRESSIVE CLIMATE CHANGE ON TITAN: IMPLICATIONS FOR HABITABILITY J. M. Moore[1] and A. D. Howard[2], [1]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035 jeff.moore@nasa.gov, [2]Dept. of Environmental Sciences, Univ. of Virginia, Charlottesville, VA 22904-4123, ah6p@virginia.edu

Introduction: Titan's landscape is profoundly shaped by its atmosphere and comparable in magnitude perhaps with only the Earth and Mars amongst the worlds of the Solar System. Like the Earth, climate dictates the intensity and relative roles of fluvial and aeolian activity from place to place and over geologic time. Thus Titan's landscape *is* the record of climate change. We have investigated three broad classes of Titan climate evolution hypotheses (Steady State, Progressive, and Cyclic), regulated by the role, sources, and availability of methane. We [1] favor the Progressive hypotheses, which we will outline here, then discuss their implication for habitability.

Progressive hypotheses have been suggested for supplying Titan's methane-rich atmosphere that do not rely on continuous replenishment. *McKay et al*. [2] considered that the warming sun may have been key to generating Titan's atmosphere over time. They hypothesize that Titan experienced a Triton-like phase 3 Gyr ago, where Titan's surface may have been covered by methane and possibly nitrogen ices. The surface would have gradually warmed as the solar luminosity increased, releasing methane into the atmosphere. *Lorenz et al*. [3] concur that nitrogen may have been collapsed out of Titan's atmosphere in the past due to the faint young sun, and/or because ancient methane was photochemically destroyed at a rate faster than it could be supplied to the atmosphere. The gradual increase in solar luminosity and irradiation-induced lowering of the surface albedo may have released frozen volatiles to the atmosphere over time. *Moore and Pappalardo* [4] argued that there have been no conclusively identified volcanic features seen on Titan, as well as reviewed the range of recent geophysical analyses indicating a cold, quiescent interior, and concluded that Titan's landscape is consistent with these theories. A simple Progressive scenario would be that Titan was Triton-like until recent geologic time when solar warming (perhaps abetted by a large impact event) rapidly created a thick atmosphere, initially with much more methane than at present, resulting in initial global fluvial erosion that has over time retreated towards the poles with the removal of methane from the atmosphere (e.g., [5,6]).

Geological Observations: The types of terrains seen on Titan may be difficult to reconcile with a simple steady-state scenario. For Titan to have still-recognizable cratered terrains *and* ongoing fluvial activity could imply one or more of at least three possible explanations: (1) alkane fluvial erosion on Titan is extremely inefficient relative to that by water on the Earth and Mars; (2) fluvial erosion very rarely (or briefly) occurs on some regions on Titan; and/or (3) it has started raining on Titan only in geologically recent times. We [7] proposed that Hotei and Tui Regiones are sites of sub-equatorial paleo-lakes, and they suggested the loss of low-latitude lakes was due to irreversible loss of methane available for precipitation. These observations, coupled with the latitudinal distribution of landform types across Titan (incompletely eroded bedrock exposures favoring low latitudes, while the higher latitudes and poles are dominated by sediment), leads us to favor the progressive hypotheses [1].

Implications for Habitability: If indeed Titan's present climate is only a few hundred of millions—or even a few tens of millions [8]—of years old, the ability of self-replicating and metabolizing organisms on or just beneath the surface (in the lakes, aquifers, or otherwise) to reach such states of organization may be challenged. If such organisms *do* exist, then though they would presumably be very different in chemistry than terrestrial organisms, their existence could be taken as an indication that life (even unlike we know it) can arise very quickly. The other possible challenge to the rise and sustenance of such organisms posed by the progressive hypotheses is that cryo-volcanism or other sources of internal heating at or near the surface, are not required (and may not exist), calling into question whether essential energy gradients capable of supporting metabolism would be present. (Of course, it is conceivable that atmospheric processes alone might create a biologically useable disequilibrium.) Thus, a Titan in which the present climate is a relatively modern development provides an important test for the virility of life in the cosmos.

References: [1] Moore, J.M. & A.D. Howard (2014) The landscape of Titan as witness to its climate evolution. *JGRE* (*submitted*) [2] McKay, C.P. *et al.* (1993) *Icarus 102*, 88-98. [3] Lorenz, R.D. *et al.* (1997) *Science 275*, 642-644. [4] Moore, J.M. & R.T. Pappalardo (2011) *Icarus 212*, 790-806. [5] McKay, C.P. (2010) Titan Through Time 1, p. 85. [6] Toon. B. *et al.* (2010) Nitrogen Ocean/Lakes on Early Titan (abs.), *BAAS* 42, 1077. [7] Moore, J.M. & A.D. Howard (2010) *GRL* 37, L22205. [8] e.g., Yung, Y.L. *et al.* (1984) *Astrophys. J. Supp. 55*, 465-506.

ENCELADUS' FULLY CRACKED CORE: IMPLICATIONS FOR HABITABILITY

M. Neveu[1], C. R. Glein[2], A. D. Anbar[1,3], C. P. McKay[4], S. J. Desch[1], J. C. Castillo-Rogez[5], and P. Tsou[6], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA. [2]Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Rd. NW, Washington, DC 20015, USA. [3]Department of Chemistry and Biochemistry, Arizona State University, Tempe, AZ 85287, USA. [4]Space Science Division, NASA Ames Research Center, Moffett Field, CA 94035, USA. [5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. [6]Sample Exploration Systems, La Canada, CA 91109, USA. Email: mneveu@asu.edu.

Introduction: We model numerically the geophysical evolution of Enceladus' core to constrain the temperature T, pressure P, and core cracking depth in the plume source region at depth. We investigate whether (a) the core can be hot enough to generate chemical disequilibria that could be utilized by life; (b) core T are suitable for life at water-rock interfaces in cracks.

Thermal evolution of the rocky core: Whole-moon thermal models must capture complex tidal processes that cause Enceladus' geyser activity [1], which is difficult to do. The thermal evolution of the core can be modeled with higher fidelity: since rock is less prone to tidal deformation, core heating should be dominated by radioactivity [2]. We simulated the 1D thermal evolution of the core over 4.56 Gyr using the model of [3]. We assumed a composition of either dry (R=167 km) or hydrated chondritic rock (R=197 km), a low thermal conductivity of 1 W/m/K in all cases, and a seafloor or core-mantle boundary (CMB) temperature T_{CMB} of either 273 K (buffered by water ice melting from tidal heating) or 176 K (eutectic H_2O-NH_3 melting). Fig. 1 shows geotherms at 600 Myr (black curves), when the central T is maximized, and at 4.56 Gyr (blue curves). Changing T_{CMB} to 176 K shifts the geotherms horizontally by 97 K (not shown), while the choice of core density shifts them vertically. After 600 Myr, the core undergoes secular cooling: the present central T is 265 K for T_{CMB}=176 K and 360 K for T_{CMB}=273 K. Because $T<T_{[serpentinite\ dehydration]}$ ~750 K [4] (Fig. 1), a dry core is unlikely, unless Enceladus accreted very early so that short-lived radionuclide heat could dehydrate the core (although it would first drive intense hydrothermal activity).

Core fracturing depth: Building on these results, we used a new core cracking model to estimate the fracturing depth in the core. This model allows cracks to form by thermal expansion mismatch at boundaries between grains of differing mineralogy [5], thermal pressurization of pore water [6], swelling of rock upon hydration, and crack widening or clogging by mineral dissolution or precipitation. Cracks heal if rock transitions from brittle to ductile [7]. Thermal contraction mismatch cracks the upper 20% of the core if T_{CMB} = 273 K (upper 40% if T_{CMB} = 176 K); the rest is cracked by thermal pore pressurization. Core T always remain below the brittle/ductile transition for serpentinite rock in the relevant diffusion creep regime, which prevents cracks from healing even on Gyr timescales (Fig. 1). In all cases, we find that the whole core has been cracked since its formation. Hydrothermal fluids could thus circulate throughout the core (not modeled here). These results do not yet account for mineral dissolution or precipitation. Together with core T<750 K, this leads us to expect Enceladus' core to be hydrated.

Mixed prospects for habitability below the plume source: On one hand, if the core has been geochemically altered over Enceladus' history, it may approach chemical equilibrium with the ocean. This would be unfavorable for life, unless hot spots or water/ice radiolysis create local thermal or redox gradients. On the other hand, the mild temperatures (T<360 K) in the present core would allow Earth-type microbes to potentially inhabit the entire core. Time may also matter for habitability: hydrothermal vents would have been hotter (Fig. 1) and more abundant during the first Gyr. Our core T, P, and cracking depths constraints can serve as inputs for further modeling of hydrothermal equilibrium and kinetics at the plume source.

References: [1] Hedman M. M. et al. (2013) *Nature, 500,* 182-184. [2] Schubert G. et al. (2007) *Icarus, 188,* 345-355. [3] Desch S. J. et al. (2009) *Icarus, 202,* 694-714. [4] Rutter E. H. et al. (2009) *J. Struct. Geol., 31,* 29-43. [5] Vance S. et al. (2007) *Astrobiology, 7,* 987-1005. [6] Le Ravalec M. and Guéguen Y. (1994) *JGR, 99,* 24251-24261. [7] Kohlstedt D. L. et al. (1995) *JGR, 100,* 17587-17602.

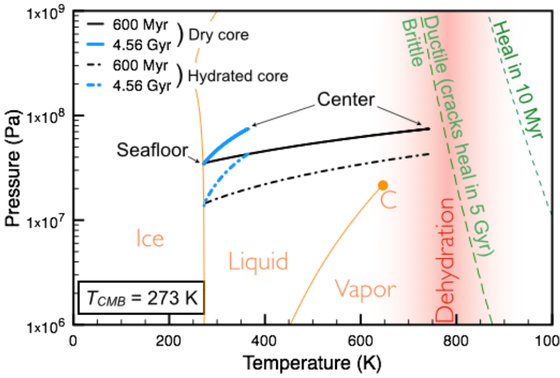


Fig. 1: Enceladus dry and hydrated core geotherms. Overlain: water phase diagram, serpentinite dehydration temperatures, and serpentine brittle-ductile transition for strain rates of (10 Myr)$^{-1}$ and (5 Gyr)$^{-1}$.

LABORATORY INFRARED SPECTROSCOPY OF TITANÔS THOLINS IN LIQUID METHANE AND LIQUID ETHANE: CAN COMPLEX ORGANICS IN TITANÔS LAKES BE DETECTED?

D. Nna-Mvondo[1], S. Singh[2], D. Mège[3,1], V. F. Chevrier[2], G. Tobie[1], and C. P. McKay[4], [1]Laboratoire de Planétologie et Géodynamique, LPG Nantes, CNRS UMR 6112, Université de Nantes, Nantes, France, delphine.nnamvondo@univ-nantes.fr, [2]Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, AR, USA, [3]Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Wrocğaw, Wrocğaw, Poland, [4]NASA Ames Research Center, Moffett Field, CA USA.

Introduction: Since the discover by Cassini ISS and SAR in mid-2005 and mid-2006 of a large dark feature in the Titan south polar region, suggestive of a lake (Ontario lacus) [1] and of a vast array of lake-like features being possibly liquid in the north polar region [2], observation of the Titanôs lakes by Radar radiometry and VIMS from the Cassini Orbiter have emerged to characterize the composition and physical properties of the polar lakes. However, currently the chemical composition of these lakes remains poorly determined, due to the presence of strong atmospheric absorptions, mainly CH_4. Theoretical models based on thermodynamic data predict liquid ethane and methane to be abundant in Titan lakes and seas [3] and other organic species from atmospheric precipitation to be additional constitutents such as complex organics including the refractory macromolecular material of Titanôs aerosols (Titan tholins). Here we present a Titanôs lakes experimental simulation in order to examine the spectroscopic signature of a liquid methane and a liquid ethane in contact with laboratory analogs of Titanôs aerosols.

Laboratory Simulation of Titanôs lakes: Experiments have been performed in the Titan simulation facility of the W.M Keck laboratory at the University of Arkansas [4]. An insulated cylindrical steel cryo-vacuum chamber (internal diameter of 61 cm and height of 208 cm) accommodates out a Titan module that sits inside a main chamber. Titan module contains a temperature control box internally and externally lined with LN2 cooling pipes allowing approaching temperatures relevant to Titan surface (90-94 K). Titan tholins synthesized at NASA Ames Research Center were introduced inside a Petri dish into the sample collection pan sit inside the module. The pressure was maintained at 1.5 bar throughout the experiments to simulate Titan atmospheric pressure at the surface. Once the required temperature and pressure was reached, the sample (methane, ethane) was introduced into the chamber and the module through a condenser using condenser input coils. The behavior of the sample was monitored via FTIR, in the near-infrared from 2.5 to 1.0 µm (4000-10000 cm^{-1}). The mass reading was also monitored.

Preliminary Results: Several spectra were acquired during the experiments: tholins in liquid methane, in liquid ethane and in liquid ethane/acetonitrile (see figure 1).

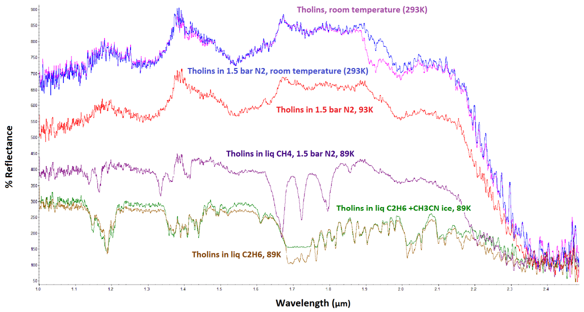


Fig. 1. Spectra of tholins alone and in solvents at low temperature (89K) acquired during the experiments.

The first results show that the tholins infrared signature totally disappears in presence of the solvents and no new absorption bands appear in the spectra. Further IR analysis of the tholins exposed to the solvents neither show modification against the initial tholin optical features. These first results seem to confirm the very low solubility/reactivity or non-solubility of Titan tholins in such solvents as predicted theoretically [5]. We have also observed that tholins when in contact with these solvents are not remaining in suspension. In this case, the refractory material of Titanôs aerosols would not be dissolved in the Titanôsurface lakes and seas but would rather sinks. However, to confirm these first data, additionnal experiments are needed and are in the prospect of our next work. One of these future experiments is to increase the initial quantity of tholins in contact with the solvents. Our experimental approach and its resulting data can be very relevant in regards to current VIMS observations of Titanôs lakes and proposed future missions to Titan like the ESAôs Titan Saturn System Mission (TSSM).

References: [1] Turtle E. P. et al. (2009) *Geophys. Res. Lett.*, *36(2)*, L02204. [2] Stofan E. R. et al. (2007) *Nature*, *445*, 61ï64. [3] Lunine J. I. et al. (1983) *Science*, *222*, 1229ï1230. [4] Wasiak et al. (2012) *Adv. Space Res. 51*, 1213ï1220. [5] Raulin, F. et al. (2012) *Chemical Society Reviews 41*, 5380ï5393.

SPECTROSCOPY, PHOTOCHEMISTRY, AND VIABILITY OF *BACILLUS SUBTILIS* SPORES AFTER UV IRRADIATION: IMPLICATIONS FOR SURVIVAL AND DETECTION AT EUROPA

A. C. Noell, T. Ely, D. Bolser, H. Darrach, R. Hodyss, P. V. Johnson, and A. Ponce
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA 91109,
aaron.c.noell@jpl.nasa.gov

Introduction: Europa is a tantalizing astrobiological target because of the possibility that its subsurface ocean is in contact with its rocky interior which allows for hydrothermal activity and the necessary conditions for life [1]. The technical challenges of remotely breaching an ice shell of unknown depth mean that for now potential missions to Europa will try to search for any clues of potential life that have made their way to the near surface, where the unforgiving temperature, pressure, and radiation surface environments of Europa await. Therefore it is critical to understand the photochemistry and viability changes of biomolecules and microbes under these unforgiving conditions in order to develop plausible detection strategies and targets.

Bacillus subtilis spores are a useful model organism for investigating the effects of UV irradiation under Europan conditions because of their relatively high resistance to a wide variety of extreme conditions in space [2], and their importance as an indicator species for reduction of forward contamination in planetary protection protocols. Furthermore, all microbial spores contain percent levels of dipicolinic acid (DPA) which is released upon germination or cell lysis, and is therefore a general high concentration biomolecule that might be detectable on Europa.

Experimental: *B. subtilis* spores and DPA were each UV irradiated in a high vacuum chamber at temperatures relevant to Europa. Spectra of both were taken with FTIR pre- and post-irradiation to observe photochemical changes after different amounts of irradiation. Spores were recovered and cultured to measure changes in the rate of UV inactivation between 100K and room temperature. Irradiation experiments were also performed with micron layers of ice cover to explore the importance of shielding VUV photons.

Results and Discussion: FTIR spectra of *B. subtilis* and DPA are presented, both in good agreement with previous work [3, 4] The UV photolysis pathway of DPA is presented for the first time including its first step as a single decarboxylation to form niacin. However, no double decarboxylation to form pyridine was observed as might have been expected. Instead unidentified photoproducts were observed after long duration (16 hrs Ar-arc lamp) irradiation. The same novel photoproducts could also be observed in the spectra of irradiated spores confirming the importance of DPA as a spectral marker of spores and as a part of their UV resistance.

Spores remained viable under UV irradiation longer at 100 K than at room temperature in agreement with previous work [5, 6]. Ice layers covering the spores did not change their photochemistry or reduction in viability compared to uncovered spores.

This work begins to constrain the potential for forward contamination of microbes under Europan conditions, and observed a 99.9% reduction in *B. subtilis* viability after ~40 hrs of irradiation at Europa. More work is needed to explore the potential for sulfuric acid or hydrated minerals in the ice to increase the shielding of the ice and extend the viability of organisms at the surface. DPA is a useful marker of spores both within the cell and once released, but will also be photolyzed into smaller fragments under Europan surface conditions.

References:

[1] De Pater, I. and J.J. Lissauer.(2010) *Cambridge University Press*.
[2] Horneck, G., et al. (2010) *Microbiol. Mol. Biol. Rev., 74*, 121-+.
[3] Carmona, P. (1980) *Spectrochim. Acta, Pt. A: Mol. Biomol. Spectrosc.*, *36*, 705-712.
[4] Johnson, T.J., et al. (2009) *Appl. Spectrosc.*, *63*, 908-915.
[5] Dose, K. and A. Klein. (1996) *Origins Life Evol. Biosphere, 26*, 47-59.
[6] Weber, P. and J.M. Greenberg. (1985) *Natur*, *316*, 403-407.

COMPARTMENTALISATION STRATEGIES FOR HYDROCARBON-BASED BIOTA ON TITAN.

L. H. Norman[1], A. D. Fortes[2], I. Crawford[3], and N. Skipper[4], [1] Dept. of Space & Climate Physics MSSL / UCL (Planetary Center, KLB, University College London, WC1E 6BT, lucy.norman.09@ucl.ac.uk), [2] Dept. of Earth Science, UCL / Birkbeck College, [3] Dept. of Earth & Planetary Sciences, Birkbeck College, [4] Dept. of Physics and Astronomy, UCL.

Introduction: The goal of our study is to determine the nature of compartimentalisation strategies for any organisms inhabiting the hydrocarbon lakes of Titan (the largest moon of Saturn). Since receiving huge amounts of data via the Cassini-Huygens mission to the Saturnian system astrobiologists have speculated that exotic biota might currently inhabit this environment. The biota have been theorized to consume acetylene and hydrogen whilst excreting methane (1,2) leading to an anomalous hydrogen depletion near the surface; and there has been evidence to suggest this depletion exists (3). Nevertheless, many questions still remain concerning the possible physiological traits of biota in these environments, including whether cell-like structures can form in low temperature, low molecular weight hydrocarbons.

The backbone of terrestrial cell membranes are vesicular structures composed primarily of a phospholipid bilayer with the hydrophilic head groups arranged around the periphery and are thought to be akin to the first protocells that terrestrial life utilised (4). It my be possible that reverse vesicles composed of a bilayer with the hydrophilic head groups arranged internally and a nonpolar core may be ideal model cell membranes for hydrocarbon-based organisms inhabiting Titan’s hydrocarbon lakes (5). A variety of different surfactants have been used to create reverse vesicles in nonpolar liquids to date including; non-ionic ethers (7) and esters (6, 8); catanionic surfactant mixtures (9); zwitterionic gemini surfactants (10); coblock polymer surfactants (11); and zwitterionic phospholipid surfactants (12).

In order to discover whether certain phospholipids can exhibit vesicular behaviour within hydrocarbon liquids, and to analyse their structure, we have carried out experimental studies using environmental conditions that are increasing comparable to those found on the surface of Titan. Experimental methods that have been used to determine the presence of vesicles include the use of microscopy (see Fig.1 for an example), the presence of the Tyndall scattering effect, transmission electron microscopy (TEM), dynamic light scattering (DLS), small-angle neutron scattering (SANS) and small-angle x-ray scattering (SAXS). These studies are currently being anaylzed, however, some results have indicated the presence of reverse vesicles in certain systems. Compounds that are shown to form reverse vesicles in conditions comparable to those of Titan‘s lakes could be potential ‘biomarkers’ and searched for in future missions to Titan.

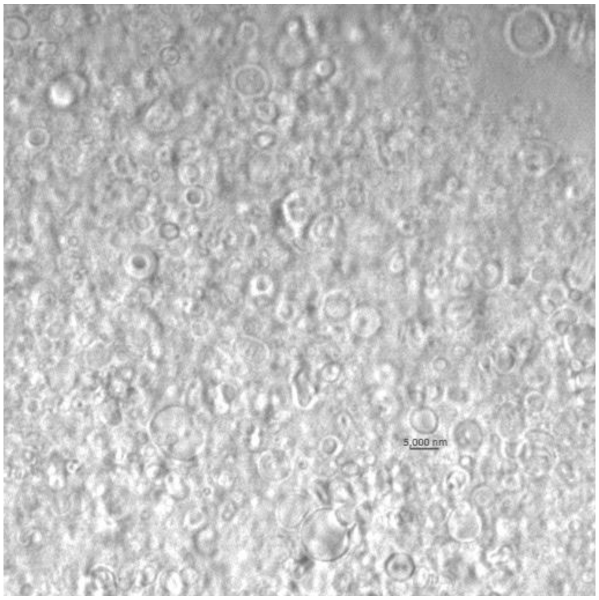


Fig.1. Micrograph of uni- and multi- lamellar reverse vesicles formed from phosphatidylcholines (primarily C4 & C18) and NaCl in cyclohexane.

References: [1] Schulze-Makuch D. et al. (2006) *Orig Life Evol Biosph, 36,* 324. [2] McKay C. P. et al. (2005) *Icarus 178,* 274. [3] Strobel D. F. (2010) *Icarus 208*, 878. [4]. Fiordemondo D. et al. (2007) *Chem. Bio. Chem. 8*, 1965. [5] Norman L. H. And Fortes A. D. (2011) *A&G 52*, 39. [6] Mollee H. et al. (2000) *J Pharm Sci, 89*, 930. [7] Kunieda H. et al. (1999) *Langmuir, 15*, 3118. [8] Shrestha L. K. et al. (2006) *Langmuir, 22*, 1449. [9] Li H. G. et al. (2007) *Chem. Lett, 36*, 702. [10] Peresypkin A. et al. (2007) *Mendeleev Commun., 17*, 82. [11] Rangelov S. et al. (2004) *J. Phys. Chem B, 108*, 7542. [12] Tung S. H. et al. (2008) *J. Am. Chem*., *130*, 8813.

Acetylene fermentation: Relevance to primordial biogeochemistry and the search for life in the outer solar system.

R.S. Oremland, S.M. Baesman, and L.G. Miller

Acetylene is a highly reactive component of planet(oid)s with anoxic, methane-rich atmospheres, such as Jupiter, Saturn, Titan, and perhaps the primordial Earth. Included in this group is Enceladus, although it is not clear if the acetylene detected within its jets by Cassini was formed by photolysis of methane or from thermo-catalysis of organic matter in the orb's interior. Acetylene inhibits many microbial processes (e.g., methanogenesis, methane oxidation, hydrogen metabolism, denitrification) yet a number of anaerobes can use it as a carbon and energy source to support growth. The best studied is *Pelobacter acetylenicus*, which carries out a two-step reaction involving the enzymes acetylene hydratase and acetaldehyde dismutase. The former, a low potential W-containing enzyme, forms acetaldehyde while the latter produces ethanol and acetate. Metabolism of acetylene by mixed microbial communities (sediments and/or enrichment cultures) produces these intermediates, and when coupled with sulfate-reduction or methanogenesis respectively forms CO_2 or an equal mixtures of CO_2 plus CH_4. It is not inconceivable that such an anaerobic, microbial food chain could exist in the waters beneath the ice cap of Enceladus, Titan, or even in the mesothermal atmospheric regions of the gas giants. Detection of the identified intermediate products of acetylene fermentation, namely acetaldehyde, ethanol, acetate and formate in the atmospheres of these planet(oid)s would constitute evidence for a microbial life signature. This evidence would be strongly reinforced if a stable carbon isotope fractionation was identified as well, whereby the products of acetylene fermentation were enriched in ^{12}C relative to ^{13}C (i.e., had a lighter $\delta^{13}C$ signal) when compared to that of the starting acetylene. The most practical target to test this hypothesis would be Enceladus, owing to the relative ease of sample collection and analysis either in future flybys or lander/collector missions.

EUROPA. R. T. Pappalardo, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 321-560, Pasadena, CA 91109.

Europa is an astrobiological and geophysical wonderland. Galileo spacecraft data suggest that a global ocean exists beneath its frozen ice surface. Specifically, magnetometry data indicates an induced magnetic field at Europa, implying that a salt-water ocean exists today. A paucity of large craters argues for a surface on average only ~40–90 Myr old, and two multi-ring structures suggest impacts punched through an ice shell ~20 km thick. Europa's ocean and surface are inherently linked through tidal deformation of the floating ice shell. Processes whih defom the ice shell (notably tidal flexing, nonsynchronous rotation, and polar wander) may generate stresses that fracture and deform the surface to create fractures, ridges, and bands. Dark spots, domes, and chaos terrain are probably related to tidally driven ice convection, along with partial melting within the ice shell. Europa's geological activity and probable ocean-mantle contact may permit the chemical ingredients necessary for life to be present within the satellite's ocean. Fascinating geology and geophysics, combined with high astrobiological potential, make Europa a top priority for future spacecraft exploration.

Habitability of Enceladus: Planetary Conditions for Life

C. Parkinson

The presence of a plume on Saturn's moon Enceladus offers a unique opportunity to sample the interior composition of an icy satellite, to look for interesting chemistry and possible signs of life. We hypothesize that Enceladus' plume, tectonic processes, and possible liquid water ocean may create a complete and sustainable geochemical cycle that may allow it to support life. Given strong evidence for surface/ocean material exchange yielding crustal recycling on time scalea of 1 to 5 Myr provides compelling evidence supporting the view of a geochemical cycle, essential for originating and sustaining life.

The University of Michigan DSMC (Direct Simulation Monte Carlo) model has been adapted to include the microphysical cloud modeling algorithms necessary to realistically simulate ejection of plume particles from the vent. Tracing the particles' ballistic trajectory from multiple vent sources for those particles following a path from the vent back to the moon's surface can be used to construct a "methanol map," which when compared to Cassini observations can yield vital clues as to whether the methanol is from an internal primordial or chemically formed due to intense radiation of CH4 and H2O on the moon's surface. This has subsequent implications for the formation, evolution, and astrobiological potential of Enceladus. Specifically, the understanding the source of surface methanol not only has consequences in terms of understanding physical processes of the subsurface/surface vent hydrogeochemical system but also can give clues as to the history of Enceladus, including formation processes and conditions for habitability and planetary conditions for life.

ANALYSIS OF RIDGE TERRAINS ON ENCELADUS AND EUROPA. D. A. Patthoff[1], R. T. Pappalardo[1], H. Chilton[1,2], and P. C. Thomas[3], [1]M/S 183-821, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, Patthoff@jpl.nasa.gov, [2]Departments of Physics and Geology, California State University Fullerton, Fullerton, CA 92831, [3]Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853.

Introduction: Many icy satellites of the outer solar system show signs of either ongoing geologic activity or an extended period of deformation after the moon was formed. The deformation is plausibly related to the tidal deformation the satellites experience, for example due to either a present or a past elliptical orbit around their parent planets, and commonly takes the form of ridge and trough terrains. Ridges can take on different morphological forms such as a single or double ridge, or a ridge complex, can stand up to a few hundred meters high, reach widths of 2-20 kilometers, and extend to over a thousand kilometers long [1-5]. Despite the prominence of ridges among the satellites of outer solar system, the nature of their formation remains incompletely understood. Several models of ridge formation have been investigated for Europa, where most models involve bringing deeper material to the surface, either through tidal squeezing [6], diking events [7], upwarping related to diapirism [8], or compression along fractures [9]. These deeper layers are important for understanding the geological evolution and internal structures of icy satellites. Understanding the internal composition and structure, especially determining if and where there is liquid water within or beneath the ice shell, is important for evaluating an icy satellite's astrobiological potential. Here we use a comparative planetological approach to categorize ridges, with the goal of constraining ridge formation mechanisms across multiple icy satellites.

Methods: Our analysis expands on previous geologic mapping of ridges on icy satellites [3, 4, 10, 11], with a focus on Enceladus and Europa, to determine if the ridges are related to one another in terms of their structure, evolution, and implied formation mechanisms. Geological mapping assists in the classification of ridge types through comparisons of basic characteristics, such as planform shape, cross-sectional shape, length, height, width, and slope. The mapping can also identify common geological associations, as well as crosscutting relationships which can be used to determine the relative ages of ridges and a possible sequence of ridge formation.

Limited stereo data exists for both Europa and Enceladus. Moreover, high resolution topography for Enceladus can be obtained through analysis of limb images. In places, local topography can be determined from limb images to a resolution of 10s of meters, and ridge slopes can be determined with better precision than through shadow measurements. We utilize a series of high-resolution limb profiles that cut across ridges in Enceladus's trailing hemisphere (notably the ridges Ebony and Cufa Dorsum) and in the leading hemisphere, to determine the heights and slopes of ridges in those regions.

Ridges of Enceladus: We have identified multiple ridge types on Enceladus, double ridges in the South Polar Terrain (at the tiger stripes), and single ridges and ridge complexes on the trailing and leading hemispheres, respectively. The tiger stripe ridges are ~100 m high and 2 km wide [12] and are the youngest features in the region. Preliminary analysis of the limb images shows that prominent ridges in the trailing hemisphere ("dorsa") stand ~370 - 480 m above the surrounding terrain and have slopes of ~6° -35° on their outer flanks.

Discussion Here we seek to classify the types of ridges on Enceladus and to identify key characteristics that constrain their origin(s). We also compare them to ridges on Europa, to consider the implications for subsurface water and potential habitability. For example, the tiger stripe ridges of the South Polar Terrain resemble double-ridges, similar to those on Europa. Ridges that are similar from one moon to the next invite consideration of an analogous formation mechanism, The similarities and differences among ridges on both satellites will help to constrain the tectonic and volcanic histories of the moons and could help to determine if the moons experienced similar evolutionary paths.

References:

[1] Geissler, P.E. et al. (1998) *Icarus, 135,* 107-126. [2] Prockter L.M. et al. (2005) *GRL, 32.* [3] Bland, M.T., et al. (2007) *Icarus, 192*, 92-105. [4] Kattenhorn, S.A. & Hurford, T. (2009) *Europa*, 199-236. [5] Prockter. L.M. & Patterson, G,W. (2009) *Europa*, 237-258. [6] Greenberg, R., et al. (1998) *Icarus, 135*, 64-78. [7] Turtle, E.P., et al. (1998) *Eos Trans*, abs. F541. [8] Head, J.W., et al. (1999) *JGR, 104* 24,223-24,236. [9] Patterson, G.W., et al. (2006) *JSG 28*, 2237-2258. [10] Kargel, J.S., Pozio, S. (1996) *Icarus, 119*, 385-404. [11] Crow-Willard, E. & Pappalardo, R.T. (2011) *EPSC-DPS*, abs., 635. [12] Prockter, L.M., et al. (2010) *Satellites of the Outer Solar System*, 61-109.

STEREO TOPOGRAPHY AND SUBSURFACE THERMAL PROFILES ON ICY SATELLITES.

C. B. Phillips, SETI Institute, Mountain View, CA. Phillips@seti.org

Introduction: Stereo topography can be used in combination with numerical modeling to study the subsurface structure and thermal history of icy satellites, with important implications for past and perhaps current habitability. We construct digital elevation models (DEMs) of Jupiter's and Saturn's icy satellites from stereo images from the Galileo SSI and Cassini ISS instruments using the software programs Ames Stereo Pipeline and SOCET SET. We have extracted topographic profiles of craters on Europa, Rhea, Dione, and Tethys, and compared our measured crater relaxation with predictions from coupled thermal and viscoelastic models for the Saturn satellites. We also created topographic profiles of tectonic features on Dione and compared them with models of flexure.

This combination of DEM measurement and theoretical and numerical geophysical models allows us to estimate subsurface thermal profiles early in the histories of these satellites. We find compelling evidence for the presence of liquid water ocean layers beneath the icy surfaces of the satellites of Saturn at the time of impact crater and tectonic feature formation, with particularly strong evidence for Dione. Europa, where the current near-surface presence of a liquid ocean is almost certain, can be used as an endmember scenario in comparison with the Saturn satellites.

Crater Relaxation: After creating DEMs using techniques discussed previously in [1], we extracted topographic profiles of impact craters on the satellites Dione and Rhea. Using the current crater depths, we then estimated the initial crater depth and calculated the viscous crater relaxation for each crater (Figure 1). Our results show that 100 km diameter craters on Rhea range from about 10-50% relaxed, while craters with diameters greater than 200 km have relaxations of 40-50%. In comparison, craters with diameters of less than 100 km on Dione are 30-50% relaxed, while craters with diameters greater than 100 km were 60-75% relaxed. We are currently completing similar measurements for Tethys.

We then compared these observations with the results of a combined thermal and visco-elastic relaxation model based on the work of [2] and [3]. The model for Rhea (Figure 1) predicts a maximum crater relaxation that ranges from about 10% for smaller craters to 40% for larger craters. In the case of Dione (Figure 1), which is modeled as differentiated, the maximum relaxation is even less: about 5% for a smaller crater and about 10% for a larger crater. Our results thus indicate that our model underpredicts the observed relaxation on Rhea and especially on Dione. We therefore require a warmer interior early in the history of the satellites to produce the observed relaxation. Since our initial thermal models reached a maximum temperature using only warm convecting ice, in order to increase the temperature even further we need to add a layer of subsurface liquid water.

Tectonic Flexure: We have also studied the topographic profiles of tectonic features in order to use flexure to estimate the elastic thickness and therefore the heat flux. From fitting our observations of the height and distance to observed flexural bulges at two sites on Dione to theoretical models of flexure, we found that the elastic thickness ranged between 2-5 km. This is consistent with work published by [4] that suggests an elastic thickness of 1.5-5 km based on long-wavelength topography, and is roughly consistent with elastic thicknesses published for other icy satellites.

With our measurement of average strain of 0.03, we estimate a heat flux of between 25-60 mW/m2. This is far higher than the heat flux of about 4 mW/m2 expected from radiogenic heating, and is consistent with our crater studies that also require an elevated heat flux to explain the observed relaxation on Dione. We suggest that tidal heating is one way to create the inferred heat flux. A model with a 50 km thick ocean for Dione (at the time these features were formed) can produce this heat flux with an eccentricity value that is fairly close to the current eccentricity value of 0.0022. Without an ocean, an eccentricity of 0.01 or higher is required to obtain sufficient tidal heating. These results are presented in detail in [5].

Conclusions: We present two lines of evidence that suggest that a subsurface ocean was present on Dione, and perhaps also Rhea, early in their histories. We are currently working on new thermal models that incorporate subsurface oceans, and will report on the results from these models. We will also continue our work on crater profiles on Europa, and expect to expand to compare those results with Ganymede and Callisto to study past thermal profiles and subsurface oceans in the Jupiter system.

References: [1] Phillips, C. B. et al. LPSC XLIV, #2766, 2013. [2] Robuchon, G., et al. Icarus 214, 82-90, 2011. [3] Robuchon, G., and F. Nimmo. Icarus 216, 426-439, 2011. [4] Nimmo, F., et al. JGR 116, E11001, 2011. [5] Hammond, N. P., et al. Icarus, 223, 418-422, 2013.

Acknowledgements: This work was supported by the Outer Planets Research Program. CBP acknowledges the contributions of F. Nimmo, N. Hammond, J. Roberts, R. Beyer, S. Kattenhorn, and E. El Henson.

ENCELADUS: SMALL MOON, BIG POSSIBILITIES

Carolyn Porco

Enceladus, a small, 504 km-diameter icy moon of Saturn, has become a major object of interest within the discipline of astrobiology as a result of nearly a decade's worth of high-powered scrutiny by the Saturn-orbiting Cassini spacecraft. The entirety of Cassini's scientific payload – imaging science cameras, ultraviolet, near-infrared, and long-infrared spectrometers, magnetometer, dust analyzer, mass spectrometer, a host of fields & particles experiments, as well as the radio science and radar instruments – has been brought to bear in a full-frontal investigation of this body. What has been found is a region extending from high southern latitudes all the way to its south pole that is home to ~100 geysers and ~ 5GW of anomalous thermal radiation emerging from 4 long and deep prominent fractures crossing the region. A comprehensive look at these findings, informed by an already large body of theoretical work addressing them, indicates that Enceladus is very likely home to the solar system's most accessible extraterrestrial habitable zone.

In this presentation I will review what we currently know about Enceladus that makes it a viable habitable icy world.

THE ROLE OF CLATHRATE HYDRATES IN THE (BIO)GEOCHEMICAL CYCLES OF ESSENTIAL ELEMENTS OF LIFE IN THE DEEP ENVIRONMENTS WITHIN THE ICY MOONS.

O. Prieto-Ballesteros[1], and V. Muñoz-Iglesias[1,2], [1]Centro de Astrobiologia-INTA-CSIC. Ctra. Ajalvir km. 4, 28850 Torrejón de Ardoz. Madrid. Spain (prietobo@cab.inta-csic.es), [2]Universidad Complutense de Madrid, 28040 Madrid. Spain.

Introduction: Ecological niches are sustained if habitability variables of energy and nutrients are unrestricted. Assuming that the most important source of energy for organisms deep within the icy moons of the Solar System is chemical, some authors have considered the disequilibria in the oceans as the limiting factor for their habitability. In deep environments on Earth (e.g. continental rocks, or beneath the sea-floor), microorganisms take energy from anaerobic respiration, where species such as CO_2, NO_2^-, NO_3^-, SO_4^{2-}, Fe^{3+}, Mn^{4+}, are used as electron acceptors, while CH_4, H_2, N_2, organic compounds, sulfides, Fe^{2+}, and Mn^{2+}-bearing species can be electron donors. Some of these are non-polar molecules that might be trapped within clathrate lattices at certain conditions. The objective of this work is to discuss the role of clathrates as major reservoirs for the essential chemical elements for life within the icy moons, and how these putative sources behave in salty solutions at high pressure.

Sources of elements. While some tentative (bio)geochemical cycles have been discussed recently in the cases of the oceans of both, Europa and Enceladus, information is scarce for the conditions of deeper liquid reservoirs such as those in Ganymede or Titan [1]. Some authors show that the hydrothermal ecosystem, which is the most popular terrestrial analogue used for Europa's ocean, depends on the oxidants provided from upper layers to persist (e.g. O_2, SO_4^{2-}, CO_2) [2]. They surmise that the ecosystems would survive in parallel than the geothermal input existence, and the alteration of the basaltic rock finish (which is the energy to maintain the disequilibria by generating oxidants); however, they did not take into account the element recycling. It has been also proposed that oxidants may come from the radiated surface in Europa, taking into account that the surface is linked to the interior in some way [3, 4]. Biogeochemical cycles of the chemical building blocks without radiolythic oxidants on this moon are suggested by [5], based on geothermal flux but some constraints about the composition of the initial rock, the outgassing of the H_2 and subsequent alkaline character of the ocean, and the disregard of the possibility of clathrate formation.

Building block elements have been also detected in the plume of Enceladus. Primary producers might be methanogens that consume H_2 in the ecosystems of this Saturn's moon [6]. The gas is produced by the serpentinization of olivine of the rock, like in massive basalts of terrestrial systems (e.g. Twin Falls, Idaho, [7]). Recent investigations about deep environments support the important role of the hydrogen as the primary substrate to start a chemosynthetic ecosystem [8, 9].

Clathrates as major sinks. In addition to the carbonates, clathrates are part of the carbon cycle of the Earth. In fact, large amounts of hydrocarbons are stored where conditions may conduct the formation of these minerals (high pressure and low temperature), which occur mostly in seafloor sediments. These physical conditions prevail in the potencial oceans of icy satellites, thus clathrates possibly constitute the dominant sink for many non-polar molecules. Regarding carbon, it may be outgassed from inside the moons as different species like CH_4 or CO_2. It is proposed that clathrates are the source for the CH_4 detected on the Titan [10], and the origin of some of the volatiles (e.g. CO_2,CH_4, and N_2) of the Enceladus' plume [11].

The presence of clathrates is related to the (bio)geochemistry of terrestrial environments in several respects such as: their stability is sensitive to the pressure and temperature changes of the environment; they may abruptly release/sequester nutrients; the released guest molecules may alter the physical-chemical conditions of the aqueous solution (e.g. pH); their formation generates heat because is an exothermic process. Similar relationships can be assumed to happen in the icy moons' environments, including deep salt-rich aqueous systems. The solubility of the volatile molecules in liquid water constrains the formation of clathrates. The presence of salts alter the solubility of gasses by lowering the activity of water in the coexisting liquid phase, causing the formation of clathrates at lower temperatures and higher pressures compared to their formation in pure water. The salting-out effect during clathrate formation may produce instabilities that strongly affect the system. Thus, salts affect to the efficiency and persistence over time of the clathrates as part of the (bio)geochemical cycles in deep environments.

References:[1] Simankov (2005) *in Origins*, Seckbach J. ed. 647-665. [2] Gaidos et al. (1999), *Science 284*, 1631-1633. [3] Chyba (2000), *Nature 403*, 381-382. [4] Hand et al. (2006), *Astrobiology 6*, 463-482 [5] Zolotov and Shock (2004), *Astrobiology 6*(1) 162. [6] McKay et al. (2008), *Astrobiology 8*, 909-919. [7] Chapelle et al. 2002. *Nature 415*, 312–315 [8] Hoehler (2005), *Met Ions Biol Syst*. 43, 9-48. [9] Wächterhäuser (1990), *Proc. Nat. Acad. Sci. USA 87*, 200-204 [10] Lunine and Atreya (2008), Nature Geoscience 1, 159-164 [11] Kieffer et al. (2006), *Science 314*, 1764-1766.

DIAPIRIC DYNAMICS: BRINGING AQUEOUS SOLUTIONS TO EUROPA'S SURFACE.

Lynnae C. Quick, NASA-Goddard Space Flight Center, Planetary Geodynamics Laboratory, 8800 Greenbelt Rd., Greenbelt, MD, 20771

Introduction: Several models for the formation of chaos and lenticulae, and for the emplacement of putative cryovolcanic features on Europa call for the transport of liquid water and/or aqueous solutions to the shallow subsurface via diapiric ascent [1-14]. Previous workers have considered the heat loss associated with ascending diapirs [14-15]. However, these studies neglected to couple the heat loss associated with these diapirs to their dynamics. Here we will consider the dynamics of diapiric ascent on Europa, in conjunction with the results of [14], in order to place constraints on the conditions by which aqueous melts may be delivered to Europa's shallow subsurface. Warm melt regions near the surface could serve as habitable environments that could be sampled by future missions (cf. [12]).

Model: The drag experienced by an ascending diapir and its associated velocity field are relatively unaffected by the properties of magma bodies themselves, but rather by the viscosity variation in the adjacent wall rock [16]. According to [17], in order for terrestrial magmas to reach the surface successfully, the viscosity of the wall rock, and by extension, the drag that the wall rock induces on a diapir, must be reduced along its periphery. If the specific function describing the variation of viscosity nearest the diapir is $\mu(y) = \mu_1 e^{Ay/d}$, where μ_1 is the viscosity at the magma-wall rock interface, and A is a constant describing the strength of the viscosity variation in the lithosphere nearest the diapir, the expression for ascent velocity of diapirs as a function of wall rock viscosity is well represented by:

$$v_o = \frac{2}{3}\frac{\Delta\rho g d^2}{A\mu_1} \qquad (1)$$

[16]. Here, d, the width of the softened layer of ice adjacent to the ascending diapir, is taken to be ~20% of the diapir's radius, and A ranges from 10 to 35 [16].

Preliminary Results: For Europa, the "wall rock" is lithospheric ice at 100 K, and from [14] we assume that diapirs emerging from the top of the convecting sublayer are composed of warm ice initially at ~ 250 K. Corresponding densities are 932 and 920 kg/m^3, respectively [18]. According to eqn.15 of [19], the viscosity of ice at 100 K is ~ 10^{33} Pa-sec, while that of ice at 250 K is 10^{15} Pa-sec. Taking A = 35 and assuming that d extends to about 20% of the diapir's radius [16], a plot of diapir ascent velocity as a function of the viscosity of lithospheric ice can be produced (Fig. 1). Fig. 1 shows that if traversing un-preheated lithospheric ice, diapirs of 1 km radius will ascend at most, at 10^{-9} m/s, while diapirs of 5 km radius will travel no faster than 10^{-8} m/s. Based on the work of [14], diapirs ascending at these rates will stall at least 10 km from Europa's surface, thereby preventing the delivery of warm, aqueous solutions to the near surface.

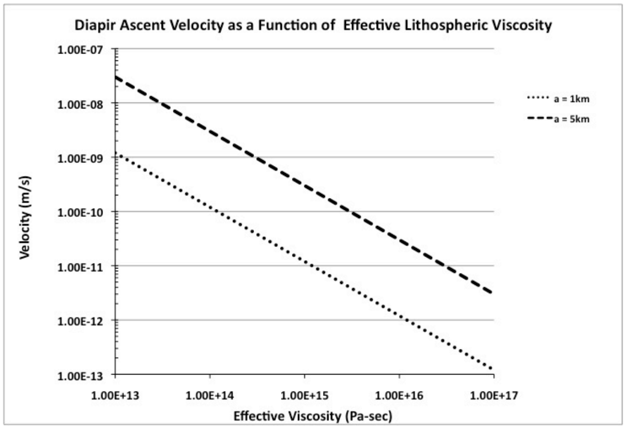


Fig. 1. Log-Log plot of ascent velocities for diapirs considered in the model for A = 15 and d ~ $0.2r_s$. Ascent velocities range from 10^{-13} to 10^{-8} m/s.

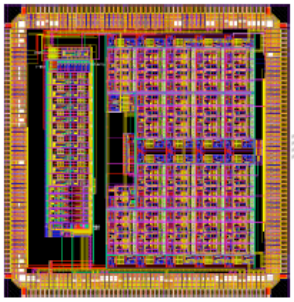
These results suggest that in order to reach Europa's shallow subsurface, aqueous solutions and cryomagmatic melts must either ascend in larger diapirs, which will melt more of the surrounding lithosphere, allowing for farther ascent, or must travel encased in preheated, less-viscous lithospheric ice, a scenario that has been suggested for viscous magmatic diapirs on Earth [16, 20]. These possibilities will be investigated in a next iteration of this model.

References:[1] Pappalardo, R.T. et al.(1998) *Nature, 391*, 365.[2] Pappalardo, R.T. et al.(1999) *JGR 104*, 24015.[3] Head, J.W. & Pappalardo, R.T.(1999). *JGR 104*, 27143.[4] Collins, G.C. et al.(2000) *JGR 105*, 1709. [5] Fagents, S.A. et al.(2000) *Icarus 144,* 54.[6] Sotin, C. et al.(2002) *GRL 29*, 1233.[7] Tobie, G. et al. (2003) *JGR 108*, 5124.[8] Pappalardo, R.T. & Barr, A.C.(2004) *GRL 31*, L01701.[9]Nimmo, F. & Giese, B.(2005) *Icarus 177*, 327.[10] Prockter, L. & Schenk, P.(2005) *Icarus 177*, 305.[11] Collins, G.C. & Nimmo, F.(2009) *Europa*, 259.[12] Schmidt, B.E. et al.(2011) *Nature 479*, 502.[13]Fagents, S.A.(2003) *JGR 108*, 5139.[14] Quick, L.C. & Marsh, B.D.(2013) *In Preparation*.[15] Quick, L.C.(2013) *Ph.D. Thesis*.[16] Marsh, B.D.(1982) *AJ Sci 282*, 808.[17] Grout, F.F. (1945) *AJ Sci 243-A*, 260.[18] Fukusako. S.(1990). *Int J Thermophys 11*, 353.[19] Barr, A.C. & Showman, A.P.(2009) *Europa*, 405.[20] Carrigan, C. R.(2000) *Encyclopedia of Volcanoes*, 219.

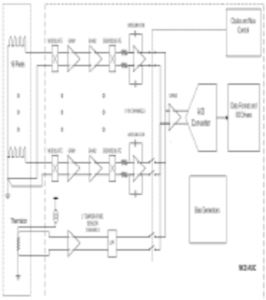
A Radiation Hard ASIC for Thermal Instrumentation on the Europa Clipper Mission.

G. Quilligan[1], J. DuMonthier[1], B. Lakew[2], I. Kleyner[1], R. Katz[1], S. Aslam[2], [1] Instrument Electronics Development Branch, NASA GSFC, Greenbelt, MD 20771, [2] Solar System Exploration Division, NASA GSFC, Greenbelt, MD 20771 (shahid.aslam-1@nasa.gov)

Introduction: One of the primary objectives of the Europa Clipper is the reconnaissance of Europa's surface with a view to identifying recently active environments. However the reconnaissance goal - which is necessary in both the scientific and engineering sense for future Europa landers is not achieved without the “enhanced payload” option, including a thermal imaging capability. The Thermal IMager for Europa Reconnaissance (TIMER), developed at Goddard, has such capability and is a multi-channel infrared radiometer, which uses miniature bandpass filters to define each spectral channel. In this abstract we describe one key hardware development at Goddard that is undergoing maturation for risk mitigation, a radiation hardened by design (RHBD) multi-channel digitizer (MCD) Application Specific Integrated Circuit (ASIC) for thermopile array readout [1]. Designed in TowerJazz Semiconductor’s 180nm CA18HD commercial CMOS process, the 5mm x 5mm chip incorporates 16 chopper stabilized readout channels with 2 temperature sensor channels, a sigma-delta (SD) ADC and a controller. The channels have variable gains and integration times allowing the user to optimize the channel SNR for a wide range of input signal amplitudes. The design uses enclosed layout transistors to harden against total ionizing dose (TID) induced leakage and diffusion guardrings to prevent single event latchup (SEL). A radiation tolerant Nyquist16-bit ADC is also included on the ASIC.



MCD die plot (5mm x 5mm)



MCD application schematic

MCD Channel Topology: To scale a sub μV level signal to a value that can be processed by an ADC requires a gain of several thousand. This high a gain can result in saturation of the gain stages due to the presence of offsets. The MCD solves this problem by first modulating (or chopping) the pixel voltages, then amplifying followed by demodulating the result. The chopping process also reduces the 1/f noise inherent in the amplifier stages. The MCD employs a chopper stabilized instrumentation amplifier scheme that has variable gain and integration times with the option to turn off chopping and/or bypass the integrator. The channel outputs are selected by a multiplexer for output to the user as a buffered analog signal and for digitization by the on-chip SD or Nyquist ADCs. To maintain flexibility, the channels are bus addressable allowing channel specific amplification schemes. Each temperature sensor channel has an associated output current source allowing an array thermistor/diode to be biased. All timing signals are synchronized to an external clock which also serves as the modulator clock for the SD ADC.

On-Chip Sigma-Delta and Nyquist ADCs: The MCD ASIC contains two ADCs. One is a 2nd order SD ADC which outputs a single bit stream which is decimated off-chip to produce a resolution of at least 16 bits, depending on the oversampling ratio. This ADC is used to digitize the channel outputs and has a relatively low input bandwidth. The other ADC is a Nyquist 16-bit pipeline converter (PADC) with the ability to sample to 20MHz. The PADC can be used for digital averaging or general purpose house keeping tasks since its inputs (differential) are also directly accessible by the user. The SD ADC is a full RHBD implementation with immunity to at least 3Mrad. The Nyquist ADC is radiation tolerant with immunity to at least 300krad. The Nyquist ADC is on the left side of the chip (see die plot) and has separate supply, clock and input-output pins.

MCD ASIC specification

Parameter	Requirement
Power	115 mW
Thermopile channels	16
Temperature sensors	2
Signal to noise ratio	> 256
TP input signal amplitude	0.1 – 120 μV
Gain (variable)	10^3-to-10^4
Chopper frequency	40-125 kHz
Noise	< 50 nV/Hz
Ambient temperature	150 -300 K
SDADC resolution	16-20 Bits
SD modulator clock rate	1 MHz
SD Nominal OSR	256
Pipeline ADC resolution	16
Pipeline ADC clock rate	1 – 20 MHz

Radiation Hardening by Design: The MCD employs ELT NMOS in all circuits (except the PADC) to increase immunity to TID. In sampling circuits where charge injection affects the performance, ELT PMOS is also used, but the majority of the circuits use standard PMOS. The main leakage mechanism is at the STI oxide interface in standard NMOS so replacing with ELT NMOS virtually eliminates the TID induced leakage.

Summary: A prototype RHBD multi-channel digitizer ASIC in a commercial 180nm CMOS process has been developed. The ASIC is expected to perform as an amplifier-digitizer up to at least 3Mrad TID with immunity to SEL. The ASIC is currently being manufactured with parts available in December 2012.

References: [1] Aslam, S., A. Akturk, and G. T. Quilligan. (2012) "A Radiation Hard Multi-Channel Digitizer ASIC for Operation in the Harsh Jovian Environment." *Extreme Environment Electronics* 849-862 [ISBN: 978-1-4398-7430-1].

GALILEO PPR OBSERVATIONS OF EUROPA: CORRELATIONS OF THERMOPHYSICAL PROPERTIES WITH EXOGENIC AND ENDOGENIC PROCESSES.

J. A. Rathbun[1], J. R. Spencer[2] and C. J. A. Howett[2], [1]Planetary Science Institute (1700 E. Fort Lowell, Tucson, AZ 85719 *rathbun@psi.edu*), [2]Southwest Research Institute (1050 Walnut Street, Suite 300, Boulder, CO 80302, USA).

Introduction: Europa is the second innermost of the Galilean satellites of Jupiter, with a relatively young, icy surface [1-3]. Thermal measurements of the surface can be used to determine whether endogenic activity is currently present on Europa, but passive processes must be understood and eliminated as a possible cause of any potentially endogenic thermal anomalies that are found.

The Galileo Photopolarimeter-Radiometer (PPR) instrument mapped thermal infrared radiation from Europa, but found no signs of endogenic activity [5, 6]. The data have, however, been used to determine thermophysical properties of the surface, which provide insight into the physical state of the surface.

Rathbun et al. [6] derived thermal inertia and bolometric albedo for 20% of Europa's surface using 13 PPR data sets, selecting those with good signal to noise and large surface coverage. They then divided the Europan surface into 10 degree square bins. For each bin, they searched the data sets for observations at different times of day. For each bin with observations at night and within 30 degrees of noon, they matched the temperature curves to a thermal model in order to determine the average thermal inertia and bolometric albedo within the bin.

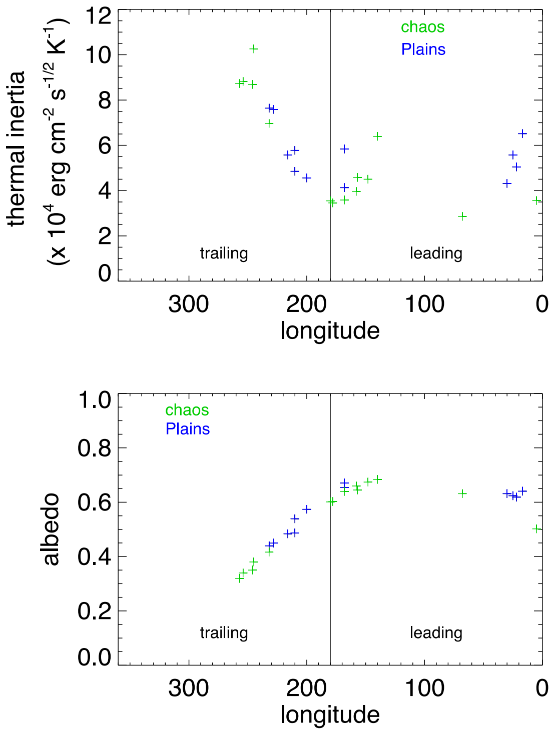


Figure 1: From [7], variation of thermal inertia and albedo with longitude and geologic unit.

New Directions: This analysis was extended [7] by including 7 additional PPR observations, which allow determination of thermal properties over a wider variety of surface longitudes. The variation of thermal properties with geologic unit was analyzed by defining several circular regions, each located entirely in a single geologic unit. The geologic map from [8] was used to define regions.

Model fits to both chaos and plains units at 2 different longitudes show that chaos has a slightly lower thermal inertia and albedo. However, thermal inertia and albedo show a much stronger correlation with longitude than with geologic unit. Thermal inertia has a minimum at 180 degrees longitude while albedo decreases with increasing longitude on the trailing hemisphere only (figure 1).

Current Study: Based on these previous studies, we will continue to model the thermophysical properties of Europa using PPR data. We will use all the PPR data sets from the previous studies and loosen constraints on the model fits. This will allow us to increase our surface coverage from 20% to closer to 50% and increase our longitudinal coverage, especially in the training hemisphere. We will shrink our bins to 9 degrees in order to minimize the mixing of geologic units in a single bin. We will compare our results to geologic units and also to exogenic processes that affect the saturnian satellites [9, 10].

References:

[1] Zanle, K. et al. (1998) *LPSC XXX*, Abstract #1815. [2] Pappalardo, R.T. et al. (1999) *JGR*, **104**, 24015-24056. [3] Schenk, P.M. et al. (2004) In: Jupiter: The Planets, Satellites and Magnetosphere, 427-456. [4] Pappalardo, R.T. (2011) *LPSC XLII*, Abstract #1635. [5] Spencer, J.R. et al. (1999) *Science*, **284**, 1514-1516. [6] Rathbun, J.A. et al. (2010) *Icarus*, **210**, 763-769. [7] Rathbun, J.A. et al. (2012) *LPSC XLIII*, Abstract #2610. [8] Doggett et al. (2009) *Mappers Meeting* abstract p. 81-82. [9] Howett C. et al. (2011) *Icarus*, **216**, 221-226. [10] Paranicas, C. et al. (2001) *GRL*, **28**, 673-565.

Europa's Water Vapor Plumes: Discovery with HST and Plans for JUICE-UVS Observations.

Retherford[1], K. D., L. Roth[1], J. Saur[2], G. R. Gladstone[1], F. Nimmo[3], M. A. McGrath[4], P. D. Feldman[5], D. F. Strobel[5], A. J. Steffl[6], T. K. Greathouse[1], J. R. Spencer[6], F. Bagenal[7], L. N. Fletcher[8], and the JUICE-UVS Team
[1]Southwest Research Institute (lroth@swri.edu), San Antonio, TX; [2]University of Cologne, Germany; [3]University of California Santa Cruz, CA; [4]NASA Marshall Space Flight Center, Huntsville, AL; [5]Johns Hopkins University, Baltimore, MD; [6]Southwest Research Institute, Boulder, CO; [7]University of Colorado, Boulder, CO; [8]University of Oxford, Oxford, UK.

Abstract: The exciting discovery of plumes of water vapor emanating from Europa's south pole region [1] raises new opportunities to investigate possibly habitable regions within Europa's subsurface. Two Europa flybys were included in ESA's Jupiter Icy Moons Explorer (JUICE) mission plan in anticipation of such opportunities [2,3]. Detailed investigations of Europa's atmosphere using NASA's Ultraviolet Spectrograph (UVS) contribution to the JUICE mission include searches for plumes using stellar occultations, and also using far-ultraviolet imaging scans of auroral emissions during the flyby sequences. We summarize our recent discovery of water vapor plumes, report our plan for JUICE-UVS observations to search for and study Europa's plumes, and discuss the importance such findings would have for the future exploration of Europa's potential habitability.

Far-UV Auroral Imaging: Hubble Space Telescope (HST) far-UV spectra and images of Europa's neutral oxygen 130.4 nm and 135.6 nm emissions contain a wealth of information about its molecular oxygen atmosphere [1,4,5,6,7]. Europa's magnetospheric plasma interaction generates auroral emissions, which exhibit a morphology that until recently has been difficult to interpret. STIS observations in Nov. & Dec. 2012, presented here, allow a new understanding of how Jupiter's magnetic field orientation and Europa's relation to the plasma sheet control the emission variability. Full explanations for this general behavior, including the likely role of ocean-induced magnetic fields and local atmospheric density enhancements, remain the subject of future investigations [1,7].

We have developed a technique using diagnostic spectral ratios of far-UV auroral emissions (Lyman-α : OI 130.4 nm : OI 135.6 nm) to identify water vapor emissions [1] similar to the technique that was used to initially detect the molecular oxygen atmosphere using the OI 135.6 nm : OI 130.4 nm ratio of ~2 [4]. Figure 1 illustrates the successful application of this technique in detecting Lyman-α emissions extending ~200 km above the ~75° S region, on the anti-jovian side.

High spatial resolution limb imaging using JUICE-UVS is planned for times within several hours of the closest approaches to Europa, which could directly image plume gases in a manner analogous with plume aurora imaging of Io, e.g. [8].

UVS Stellar Occultations: JUICE-UVS will use the stellar occultation technique to characterize Europa's atmosphere structure and composition and to also search for local enhancements created by plumes. This stellar occultation technique, demonstrated by Cassini-UVIS at Enceladus [9], has the benefit of being useful at relatively large distances (i.e., a few 10's of Jupiter radii) as well as during the Europa flyby sequences (i.e., a few 10's of Europa radii). A robust search for plumes is planned in JUICE's first year at Jupiter to provide a roughly 30° grid of global coverage, followed by focused targeting of likely plumes/active-regions during early and late stages of the flyby sequences.

Future Exploration: A UV spectrograph on the planned Europa Clipper mission could study the composition and variability of these plumes in more detail and would perform an even more robust global search for smaller plumes. The study of such currently active geological sites with potential connectivity to subsurface liquid water is a high priority for planetary science.

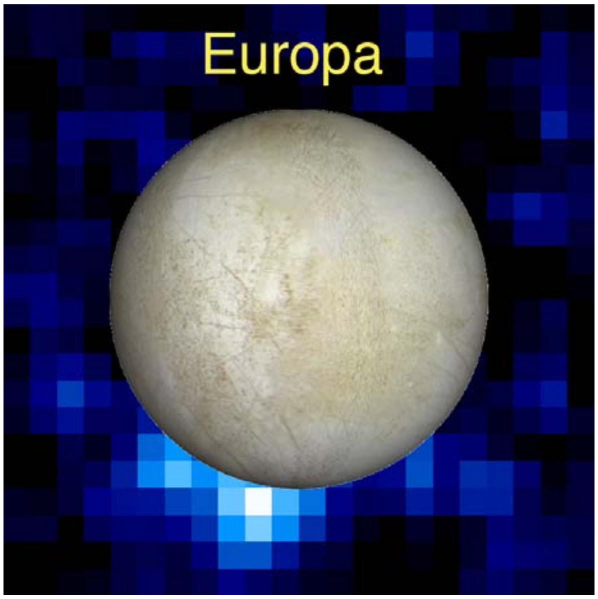


Figure 1. Illustration of the Europan water vapor plume detection reported in [1].

References: [1] Roth, L., et al. (2014), *Science in press*. [2] Grasset O., et al. (2012), *Planetary and Space Sci., http://dx.doi.org/10.1016/j.pss.2012.12.002*. [3] JUICE Assessment Study Report (Yellow Book), ESA/SRE (2011). [4] Hall, D. T., et al. (1995), *Nature*, ***373***, 677-679. [5] McGrath, M. A., et al., (2009), *Univ. of Arizona Press*, 485-505. [6] Saur, J., et al. (2011), *ApJ*, 738. [7] Roth, L., et al. (2014), *this meeting*. [8] Roth, L. et al. (2011), *Icarus*, 214, 495-509. [9] Hansen, C. J., et al. (2006), *Science*, 311, 1422-1425.

Figure 2. Illustration of a Europan water vapor plume.

DISCOVERY OF EUROPA'S WATER VAPOR PLUMES: HST UV AURORA OBSERVATIONS.

L. Roth[1,2] and K. D. Retherford[1], J. Saur[2], D. F. Strobel[3], P. D. Feldman[3], M. A. McGrath[4], F. Nimmo[5]
[1]Southwest Research Institute (lroth@swri.edu), San Antonio, TX; [2]University of Cologne, Germany; [3]Johns Hopkins University, Baltimore, MD; [4]NASA Marshall Space Flight Center, Huntsville, AL; [5]University of California Santa Cruz, CA.

Introduction. With its subsurface water ocean and relatively young icy surface Europa is a prime candidate in the search for present-day habitable environments in our solar system. The existence of water vapor plumes on Europa has long been speculated, and as discussed extensively for Enceladus and its plumes, the possible accessibility of a subsurface liquid reservoir at such plume locations has important implications for the future exploration of habitable environments.

Technique. Europa's atmosphere was initially detected by observations of its UV emissions by the Hubble Space Telescope (HST) [1]. Such observations of electron impact excited auroral emission generally provide an excellent opportunity to investigate the atmosphere and to search for water vapor plumes [2]. While optically thin in the visible, the electron excited neutral hydrogen and oxygen in Europa's environment can be observed in the UV with e.g. STIS spectral images [3] through emission at HI 121.6 nm, OI 130.4 nm and 135.6 nm. Because electron impact on H_2O yields HI 121.6 nm (Lyman-α) and OI 130.4 nm but negligible OI 135.6 nm [4], a plume could be detected by an enhanced intensity of Lyman-α and OI 130.4 nm emissions [5].

New STIS observations. We present new STIS images of the UV aurora morphology obtained during two HST visits in November and December 2012. Europa was observed at western elongation and at eastern elongation over ~7 hours, each. Both visits were designed such that Europa was exposed to the maximum variability of the magnetospheric environment. With this configuration spatially inhomogeneous, time-variable emissions caused by the periodically changing magnetospheric environment can be separated from time-stationary emission inhomogeneities.

Plume detection at Lyman-α and OI130.4 nm. The new STIS images show that Europa's global oxygen aurora is generally correlated to the orientation of the local Jovian magnetic field. In addition to these time-variable oxygen emissions the December 2012 STIS images include statistically significant and coincident surpluses in the hydrogen Lyman-α and oxygen 130.4 nm emission lines (Fig. 1). These surpluses are found persistently in the same area above the anti-Jovian south polar limb over the 7 hours of observation, indicating an atmospheric rather than plasma inhomogeneity. The relative brightnesses of the H and O emissions are indicative of electron impact dissociative excitation of H_2O and suggest two 200 km high water vapor plumes with column densities of $\sim 10^{20}$ m^{-2} [5].

The plumes were detected only in December 2012 when Europa was around the apocenter of its orbit. During the November 2012 visit and previous STIS observations from 1999 Europa was close to pericenter and no plume signal was observed [5]. Model calculations for stresses experienced by the mapped surface fractures in the south polar region agree with this observed plume variability similar to the observed variability at Enceladus [6]. Tensile stresses are stronger around apocenter, which presumably drives opening of faults and escape of water from the subsurface.

Once confirmed, these newly discovered plumes on Europa provide an excellent target for future comparative studies with Enceladus and other potentially habitable environments in the solar system.

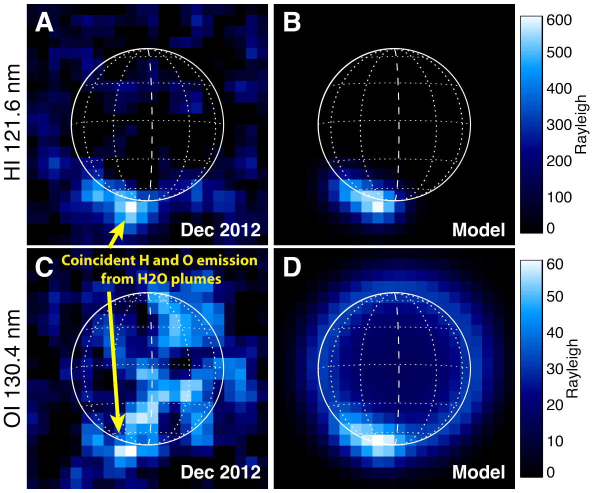


Fig. 1. Water vapor plume detection in STIS images: The coincident OI 130.4 nm and HI 121.6 (Lyman-α) emission surpluses observed at Europa's south pole (A, C) are diagnostic for water vapor. The best-fit model (B, D) suggests two ~200 km high plumes on the anti-Jovian southern hemisphere [6].

References: [1] Hall, D. T., et al. (1995), Nature, 373, 677-679. [2] Saur, J., et al. (2011), Astrophys. J., 738. [3] McGrath, M. A., et al., (2009), Univ. of Arizona Press, pp. 485-505. [4] O. P. Makarov, et al. (2004), J. Geophys. Res., 109(A18). [5] Roth, L., et al. (2014), Science, in press. [6] Hedman, M. M., et al. (2013), Nature, 500, 182-184.

The Drive to Life on Wet and Icy Worlds

Michael J. Russell, Laurie Barge and Isik Kanik
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109, USA

Life's onset on any abiotic rocky wet icy world resolves chemical and electrochemical disequilibria (Barge et al., 2012; Russell et al., 2013, and in review). The very first steps leading to metabolism are highly endergonic and thereby beyond the reach of mere geochemistry. Conversions of extraneous free energies are required to surmount these endergonic barriers. Appropriate *free energy converters*, situated in and comprising inorganic membranes harness the two main disequilibria obtaining on such worlds, driving life's emergence and its further evolution. These are i) a redox gradient of ~1 volt between the hydrothermal electron donors, hydrogen and methane, with electron acceptors such as nitrate, nitrite and/or ferric iron in an all-encompassing ocean or hydrosphere, ii) a proton gradient from ocean to hydrothermal solution across a precipitate barrier of around five units (~300 mV) to drive the emergence of biosynthesis. Carbon is fixed partly from CO_2 dissolved in and partly from CH_4. Redox bifurcating catalysts involving molybdenum are involved in both steps, coupling exergonic reactions with lesser endergonic reactions. The free energy converters or auto-mechano-catalysts comprised, and were housed by, the iron-rich layered mineral barriers spontaneously formed from precipitates composing hydrothermal mounds generated on ocean floors, where alkaline hydrothermal solutions met the carbonic hydrosphere. Those exergonic reactions that ensue are generally best served in alkaline solution. The layered double hydroxide, fougerite (~$Fe_2(OH)_5$), maybe common to both mechano-catalysts. The fuel (electron donors H_2 and CH_4) is delivered from exothermic serpentinization reactions – reactions that feed back to augment the thermal gradient driving the open system hydrothermal convection cells supplying the submarine mound. The discovery that a strain of *Methanosarcinales* currently processes these same electron donors, possibly using just this oxidant (nitrite) and emitting just this waste product (acetate), is taken as support for this model (Brazelton et al., 2011).

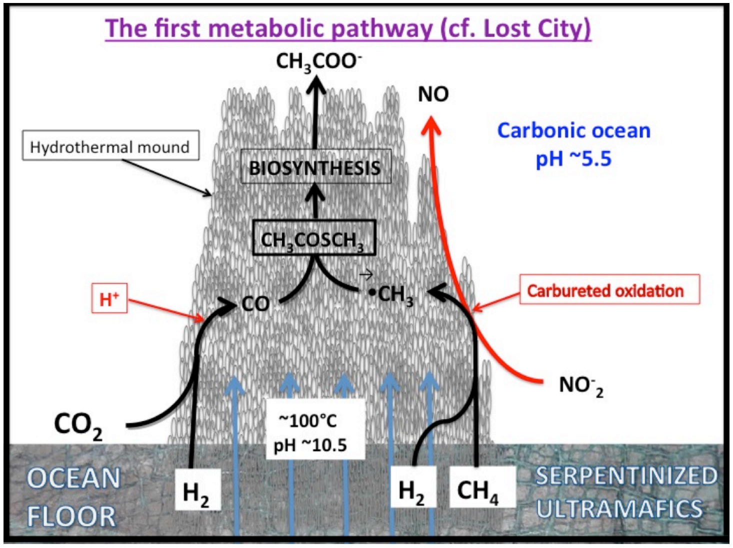


Fig. 1: *Serpentinization generates H_2 and CH_4 which are transferred in alkaline hydrothermal solution toward the outer margins of a growing submarine hydrothermal alkaline mound, Here they interact with electron acceptors nitrite and CO_2 in oceans via Ni-Fe sulfides and redox-active green rust (cf. brucite at Lost City). The entire system is predicted to culminate in a particular metabolic pathway – denitrifying methanotrophic acetogenesis – on any wet and icy globe (Russell et al. 2013).*

Barge, L.M., Doloboff, I.J., White, L.M., Russell, M.J., Kanik, I. 2012, Characterization of Iron-Phosphate-Silicate Chemical Garden Structures. *Langmuir*, 28, 3714–3721.

Brazelton W. J., Mehta M. P., Kelley D. S. and Baross J. A. (2011) Physiological differentiation within a single-species biofilm fueled by serpentinization. *Biology* 2(4). http://dx.doi.org/ 10.1128/mbio.00127-11.

Russell, M.J., Nitschke, W., Branscomb, E., (2013) The inevitable journey to being. *Phil Trans R Soc Lond* B368:20120254.

Russell, M.J. et al. (in review) The Drive to Life on Wet and Icy Worlds. *Astrobiology.*

DOES IMPACT CRATER MORPHOLOGY, GLOBAL TOPOGRAPHY AND COLOR OF AN ICY BODY BETRAY ITS HABITABILITY?

P. Schenk[1], [1]Lunar & Planetary Institute, Houston, TX (schenk@lpi.usra.edu).

Introduction: Icy bodies by their nature are locked puzzle boxes. The most habitable regions, i.e., their oceans) are essentially inaccessible, and so we must rely on indirect means to determine, a) whether they have an ocean, b) whether the ocean is close to the surface, c) and whether the inner "core," ocean and icy shell are geologically interacting.

The title asks whether impact morphologies, topography and color of icy bodies betray if it is habitable. This question is of some significance for icy bodies in our neighborhood but also those around extra-solar planets (although the availability of such data is unlikely in the near future). We now have a library of data on more than a dozen major icy worlds in our own Solar System and can partially answer the question posed, but we cannot know the answer until we complete our exploration by determining whether any of the icy bodies inferred to have oceans are actually supporting organic processes. Nonetheless, the efforts to answer this question might reveal unanticipated answers of their own.

Impact Crater Morphologies: Impact morphologies have been shown to be strongly dependent on the physical state of the icy lithospheres formed in, primarily thermal state and thermal gradient. The most dramatic examples are Ganymede, where anomalous landforms are attributed to ancient high heat flow [1], and Europa, where multi-ring landforms at small diameters are attributed to near penetration of the icy shell [2]. Thus, impact morphologies provide a direct test, offered by nature, of whether a liquid ocean resides near the surface of an ice world. Unfortunately, two other ice worlds inferred to have oceans have no craters large enough to make this test. The very thermal conditions associated with these active worlds have erased the cratering record that would reveal such morphologies. Ceres and Pluto offer the only remaining opportunities to test this hypothesis.

Global Topography: Ocean worlds are by their nature relatively warm and warm ice cannot support large variations in topography, due to lateral flow of ice in response to gravitational loads. Europa, Enceladus and Triton offer the clearest examples, where local topography does not exceed 1 km anywhere [e.g., 3, 4], and the apparent global deviation from the spheroid does not exceed 2 km [5]. Viscous relaxation also reduces topography [e.g., 6] and disentangling the signatures of these processes requires data analysis.

A key question is whether an ocean froze over and left a fossil topographic signature of its presence in the ancient past. The low dynamic range of topography on Mimas, Tethys, Dione and Rhea [+/- 5 km] (as compared to Iapetus [+/- 15 km]), suggests that all of these bodies underwent strong thermal heating early in their histories that Iapetus did not. Whether they were ever liquid inside is not clear. Although icy world topography indicates thermal state and/or presence of an ocean it cannot say anything about ocean chemistry.

Global Color: We now have rich global data sets on the NIR-UV colors of icy satellites. This is especially true for Jovian and Saturnian satellites (although the Galileo camera did not include a UV filter). Mid-IR data are also available and provide key spectroscopic identification of surface components. The nature origin of surface chemistry of Europa, for example, remains enigmatic [7]. These are key to identifying ocean chemistry in areas where such material has been brought to the surface (e.g., deep impact craters).

Although all the icy satellites mapped so far have rich color signatures, these are usually a combination of inherent compositional components mixed with exogenic magnetospheric implantation and alteration effects [e.g., 8]. The idea here is that color complexity betrays internal complexity. Inactive worlds like Callisto, Rhea and Mimas are dominated by original (accretional?) compositional signatures and space weathering. Europa and Enceladus both have strong local and regional color variability linked to deformation of the icy shell, including evidence of upwelling and exposure of deep icy materials, and possibly ocean materials as well.

The degree to which any of these aspects (crater morphology, and global color and topography) can be used to infer the habitability of an ocean world remains to be seen. Certainly, all such tools must be brought to bear on the question. The only way to insure that such tools are useful is to understand the geophysical and geochemical make-up of the icy worlds in our own back yard.

References: [1] Schenk P. et al., (2004) in Jupiter, Cambr. Univ. Press. [2] Schenk, P., and E. Turtle. (2009) in *Europa*, Univ. Ariz. Press. [3] Schenk, P., and R. Pappalardo. (2004) *Geophys. Res. Lett.,* 31, 2004GL019978. [4] Schenk, P., and W. McKinnon. (2009) *Geophys. Res. Lett.,* 36, L16202. [5] Nimmo, F., and P. Thomas. (2007), *Icarus*, 191, 182-193. [6] White, O. et al. (2013) Icarus, 171, 421-433. [7] Dalton, B., et al. (2013) *J. Geophys. Res.* 117, E03003. [8] Schenk, P., et al. (2011) *Icarus*, 211, 740,757.

A CHAOS CONVEYOR BELT?

B. E. Schmidt[1], B. Gooch[2], K. M. Soderlund[2], G. W. Patterson[3], C.C. Walker[1], P. M, Schenk[4], D. D. Blankenship[2], [1]School of Earth & Atmospheric Sciences, Georgia Institute of Technology, (britneys@eas.gatech.edu). [2]Institute for Geophysics, University of Texas, [3]Applied Physics Laboratory. [4]Lunar & Planetary Institute.

Introduction: With an icy exterior covering a global ocean, Europa has long been a target of interest in the search for life beyond Earth. Europa exists in a dynamic environment, subject to intense irradiation, impact and material veneer from it's neighbor Io, as well as immense tides from Jupiter. These processes deliver thermal and chemical energy that could be critical to supporting a putative biosphere. In the past few decades the debate about habitability of Europa has been focused strongly on the thickness of the ice shell. However, an arguably more critical question is: how does the ice shell recycle? New analysis of Europa's enigmatic "chaos terrains," indicates that these features form in the presence of a great deal of liquid water, in some regions comparable in volume to the Great Lakes, and that this water exists within 3km of its surface [1]. The detection of shallow subsurface "lakes" implies that the ice shell is recycled rapidly and that Europa may be currently active. This new perspective has important astrobiological implications.

Lake and Ice Habitats: Melt lenses are intriguing as potential habitats, particularly the larger features, since the duration of water is on the order of a few hundred thousand years [1]. Moreover, their formation requires the existence of impurities within the upper ice shell that may be sources of energy for microorganisms. Geomorphic evidence also exists for brine movement [1,2] that can disperse fluids both vertically and horizontally through pores and fractures. This process, observed in terrestrial ice shelves, may preserve liquid water within the ice matrix over many kilometers from the source. Such motion is a means of material transport through the shell, and depends strongly upon its impurity content. Constraints from morphology indicate that brine densities may reach ~1200 kg/m^3 in regions where the ice is between 10-35% porous [1]. This provides not only an estimate of the space available for potential microorganisms, but also bounds on the chemistry within the ice. Horizontal transport of material may produce interconnectivity between distinct regions of Europa, providing a pathway for transferring nutrients and biomass, thus preserving habitable conditions within the ice over a longer duration.

Material Exchange: At a surface age of 40-90 Myr [3], and about 50% covered by chaos terrain, Europa's resurfacing rate is likely to be very high if water does play a significant role in their formation. Because of the vigor of overturn implied by the lens-collapse mechanism for forming chaos (see also abstract by C. Walker & B Schmidt, this meeting), it is likely that surface and subsurface materials are well-mixed within the largest and deepest lenses, providing a mechanism for bringing oxidants and other surface contaminants to the deeper ice shell where it can reach the ocean by convective or compositional effects. The timescales over which large lenses refreeze (a few hundred thousand years) are large compared to the timescales for vertical transport (a few tens of thousands of years [4]), while the timescales for smaller lenses are comparable to or shorter than convective timescales but involving smaller impurity loads than for larger more well-mixed sources. Moreover, marine ice accretion at the bottom of the ice shell may be contributing to a compositional buoyancy engine that would change the makeup of the ice shell [e.g. 1, 5].

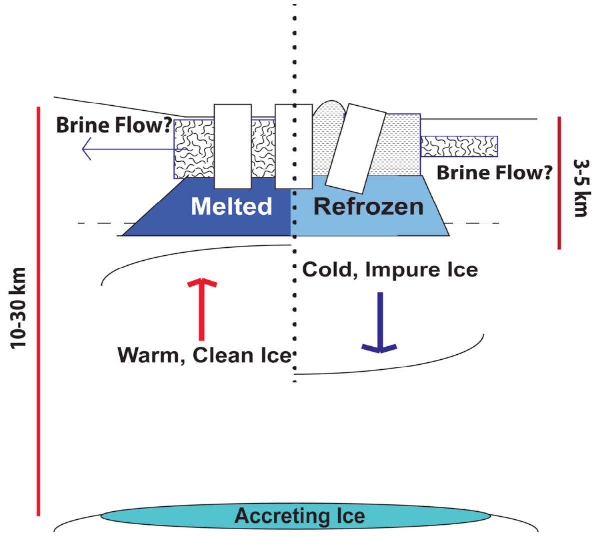


Figure 1: Schematic overview of potential material redistribution during the evolution of Europa's chaos terrain, forming a "chaos conveyor belt."

From this point of view, we evaluate the habitability of Europa's ice and ocean in light of active processes, including the lifetime of liquid reservoirs, vertical and horizontal material transport, and the resurfacing rate of the body that may form and influence shallow habitats that could be detected by Europa Clipper.

References: [1] Schmidt, B. E. et al. (2011) Nature 479 502-505. [2] Head, J.W., R. Pappalardo, (1999) JGR, 104, 27143. [3] Bierhaus, E. B. et al. (2009) in Europa, Tucson: The University of Arizona Press, 161-180. [4] Pappalardo, R. and Barr, A. C. (2004), GRL 31, L01701. [5] Soderlund, K.M. et al., (2013) *Nature Geosci*, doi:10.1038/ngeo2021.

ICY WORLD SCIENCE AND HABITABILITY IN THE NATIONAL SCIENCE OLYMPIAD FOR MIDDLE SCHOOL STUDENTS.

Dustin M. Schroeder[1], Claire B. Burch[2], Krista M. Soderlund[1], Cyril Grima[1], Donald D. Blankenship[1], Thaddeus D. Komacek[3], Terrence M. Quinn[1], Mark A Van Hecke[4], Britney E. Schmidt[5], G. Wes Patterson[6], Jeffery J. Plaut[7], [1]University of Texas Institute for Geophysics, Austin, TX, [2]Mira Loma High School, Sacramento, CA, [3]University of Arizona Lunar and Planetary Laboratory, Tuscon, AZ, [4]Science Olympiad Earth and Space Science Committee Chair, Fairhaven, MI, [5]Georgia Institute of Technology Earth and Space Sciences, Atlanta, GA, [6]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, [7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Over the past 30 years, Science Olympiad has grown from a collection of motivated high school teachers to the nation's premier team-based science competition for middle and high school students. With more than 240,000 students competing on over 6,000 teams, the National Science Olympiad provides a critical first exposure to cutting edge science for a group of geographically, economically, and ethnically diverse group of students. These students disproportionately pursue undergraduate and graduate education in science, technology, engineering, and math, often specializing in the specific subject areas in which they first competed.

This year the Earth and Space Science Committee for the National Science Olympiad has created a planetary science event, which focuses on the observation and understanding of features and processes relating to extraterrestrial ice and water in the solar system. The event – referred to simply as "Solar System" in official Science Olympiad rules, competitions, and resources – will run for two competition seasons (2013 – 2014 and 2014 – 2015) as an event for 6th through 9th grade students The event is sponsored by the University of Texas Institute for Geophysics (UTIG) which supports the national competition, scholarships for winning students, and a resource webpage hosted on the UTIG website with materials for students, teachers, and judges participating in the competition.

The Solar System event tests students on their ability to "demonstrate an understanding and knowledge of the properties and evolution of extraterrestrial ice and water in the solar system." It focuses on specific targets that include, but are not limited to: Mars (polar ice caps, equatorial glaciers, permafrost), Europa (Thrace Macula, Thera Macula, Conamara Chaos, ridges, cycloids, plains, ocean), Enceladus (plumes, tiger stripes), Iapetus, Triton, Ceres, Titan, comets, the Kuiper Belt, and the Oort Cloud. In the event, students are asked to complete one or more hands-on or interpretive tasks selected from the following topics: i. History and formation processes of specific features listed above, ii. Remote sensing, imagery, and satellite measurements of the features listed above, iii. Physical, thermal, and chemical properties of potential habitats for life, iv. Past, current, and planned future missions to explore these objects, v. Phase diagrams and different crystalline forms of water ice.

This event offers a unique opportunity for the icy world science and habitability community to coordinate outreach efforts that place information about current science, priorities, and missions directly into the hands of the nation's most passionate and talented middle school students and educators. UTIG is developing a webpage with resources for the Solar System event what will be linked directly from the National Science Olympiad webpage. These resources include an annotated bibliography of links, new middle-school level resources on specific topics, and eventually recorded webinar presentations by planetary scientists. We invite any members of the planetary science, icy world, and habitability communities that are interested in developing, editing, or hosting materials on this resource webpage to email the National Event Supervisor and UTIG sponsorship coordinator (dustin.m.schroeder@utexas.edu). We also encourage you to contact your local regional or state Science Olympiad tournament directors to volunteer as event supervisor in your local area.

THE TITAN AEROSOL SIMULANTS PRODUCED AT LOW TEMPERATURE IN THE TITAN HAZE SIMULATION EXPERIMENT AT NASA AMES: A CLOSER ANALOG OF TITAN'S AEROSOLS?

E. M. Sciamma-O'Brien[1,2*], K. T. Upton[3], J. L. Beauchamp[3], F. Salama[1], [1]NASA Ames Research Center, Moffett Field, CA (ella.m.sciammaobrien@nasa.gov); [2]Bay Area Environmental Research Institute, Sonoma, CA; [3]Noyes Laboratory of Chemical Physics and the Beckman Institute, California Institute of Technology, Pasadena, CA.

Introduction: Titan, Saturn's largest moon, is the only solid body in the outer solar system with a dense atmosphere. Because Titan's atmosphere is mostly composed of nitrogen and methane, it is often considered as a cold primordial Earth analog. Titan's atmosphere is the siege of a complex organic chemistry that occurs at temperatures lower than 200 K and leads to the production of heavy molecules and subsequently solid aerosols that form the orange haze surrounding Titan. Because the reactive carbon and nitrogen species present in Titan's aerosols could meet the functionality requirements for precursors to prebiotics (the ingredients for the building blocks of life), the study of Titan's aerosol has become a topic of extensive research in the fields of astrobiology and astrochemistry. Experiments have been developed in several laboratories in the past 30 years in order to understand the production processes and composition of these atmospheric aerosols.

The Titan Haze Simulation (THS): The THS experimental setup was developed at the NASA Ames Cosmic simulation facility (COSmIC) to produce simulated aerosols in a pulsed, supersonic jet-cooled plasma expansion. The unique characteristic of the THS is that it cools down the gas to Titan-like temperature (150 K) before inducing the chemistry by pulsed plasma[1], and that the pulsed nature of the plasma allows for a truncated chemistry that can be used to study the early stages of aerosol production, which has not been readily accomplished so far using other production methods. The study of the early stages of the chemical evolution of these simulated aerosols is critical to be able to predict the chemical functionalities present on Titan, for the development of the instruments needed for future lander missions. In addition, because the THS uses a plasma jet expansion, the gas and solid phase products of the chemistry are accelerated to supersonic speeds before being detected and/or deposited for future analyses, which is the closest laboratory simulation of a probe descent in Titan's atmosphere. The THS can therefore be used to help define which substrate and diagnostic methods are most appropriate for future missions.

Both the gas and solid phases can be monitored and analyzed. A previous *in* situ study of the gas phase has demonstrated the unique advantage of the THS to look at the first and intermediate steps of the N_2-CH_4 chemistry[2]. Due to the short residence time of the gas in the pulsed plasma discharge, only the first steps of the chemistry have time to occur in a N_2-CH_4 discharge. However by adding heavier hydrocarbon trace elements to the initial N_2-CH_4 mixture, we can observe a chemical growth evolution and study the intermediate steps of Titan's atmospheric chemistry.

Solid Phase Analyses: An extensive study of the solid phase products is presented here, and confirms the results of the gas phase analysis. In this study, THS Titan aerosol simulants were deposited on a variety of substrates for further *ex situ* analyses. The analogs were analyzed using complementary analytical techniques: infrared (IR) spectroscopy, scanning electron microscopy (SEM), nuclear magnetic resonance (NMR) spectroscopy, Direct Analysis in Real Time (DART) and Electron Spray Ionization (ESI) mass spectrometry, and visible reflectance spectroscopy for the determination of the simulants' optical constants. IR spectra of N_2-CH_4 THS simulants show the typical spectral features observed with other Titan aerosol analogs. Both DART and ESI spectra of THS simulants produced in a N_2-CH_4 mixture show, in agreement with the gas phase, that the THS aerosols are made of less complex molecules than other Titan simulants. SEM images show that grains are produced in volume in the expansion and then jet deposited onto the substrate. The grains produced in N_2-CH_4-C_6H_6 mixtures are much larger than those produced in N_2-CH_4 mixtures, consistent with a more complex chemistry when adding heavier precursors. The NMR results also support a growth evolution of the chemistry when adding heavier species to the initial N_2-CH_4 mixture. Finally, reflectance measurements in the visible led to optical constants for THS simulants that are closer to the Titan aerosol optical constants obtained from observational data by Rannou et al (2010) than any previously reported optical constants of Titan simulants produced in other experimental setups.

References: [1] Biennier, L., Benidar, A., Salama, F. (2006) *Chem. Phys.* 326, 445-457. [2] Sciamma-O'Brien, E., Contreras, C. S., Ricketts, C. L, Salama, F. (*in preparation*).

Acknowledgements: This research is supported by the NASA SMD Planetary Atmospheres Program. K.T. Upton acknowledges the support of the NASA JPFP Program.

INVESTIGATING ICY WORLD HABITABILITY THROUGH THE EUROPA CLIPPER MISSION CONCEPT.

D. A. Senske[1], R. T. Pappalardo[1], L. Prockter[2], S. Vance[1], W. Patterson[2], and the Europa Study Team, [1]Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA 91109, [2]Johns Hopkins Applied Physics Laboratory, Laurel, MD, 20723.

Introduction: Understanding the processes that lead to potential habitability across the solar system is a cornerstone of the Planetary Decadal Survey, "*Visions and Voyages*" [1]. Fundamental to this is understanding the astrobiological significance of the icy outer planet satellites. It is in this context that Europa has been placed at the forefront of outer planet exploration targets [1].

Understanding Europa's habitability is directly tied to understanding the three "ingredients" for life: water, chemistry, and energy. Our understanding of Europa suggests that it may have all three of these ingredients in the form of: (1) an extensive saltwater ocean beneath an ice shell that is geodynamically active and relatively thin (several kilometers to several tens of kilometers thick); (2) essential chemical elements derived from the primordial chondritic composition of the Jovian protoplanetary disk, plus delivery by asteroids and comets over time; and (3) a rich source of chemical energy for life created by the combination of irradiation of its surface and tidal heating of its interior. However, the processes that shape Europa's ice shell, and the exchange processes between the surface and ocean, remain poorly understood. Even the existence of a subsurface ocean, while generally accepted, is not proven.

A Europa Science Definition Team (SDT) has stated the goal for future Europa exploration as: Explore Europa to investigate its habitability. The SDT considered the objectives for a multiple-flyby mission to Europa based on current hypotheses regarding the satellite's potential for being habitable:

(1) *Ocean and Ice Shell*: Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange and the properties of the ocean;

(2) *Composition*: Understand the habitability of Europa's ocean through composition and chemistry;

(3) *Geology*: Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.

The Clipper Mission: Based on the SDT defined science drivers, a JPL-APL Europa technical team has devised a flight system and mission design that can accommodate a capable science payload to achieve these science objectives. The notional set of science instruments are: an Ice Penetrating Radar (IPR), Topographic Imager (TI), Shortwave Infrared Spectrometer (SWIRS), Neutral Mass Spectrometer (NMS), Magnetometer (MAG), Langmuir Probe (LP), and the spacecraft Radio Sub-system (RS) to enable gravity measurements. A mission design that incorporates 45 close flybys of Europa has been developed to achieve globally distributed regional surface coverage. The overall mission architecture is optimized for the mass, power, and data rate expectations of the model payload.

Reconnaissance: Science achieved by the Europa Clipper would provide global and regional characterization of the satellite. It is anticipated that a next logical step to address scientific questions regarding the habitability and composition of this icy world's subcrustal ocean would be to land a spacecraft capable of *in situ* sampling and analysis. From a recent study of a lander concept [2], it became clear that additional information is needed regarding surface characteristics and properties to robustly architect a low-risk lander concept. To maximize success of a potential future landed mission, ensuring both safe landing and access to surface material of high scientific value, surface reconnaissance is essential.

The objectives of reconnaissance are two-fold:

(1) *Site Safety*: Assess the distribution of surface hazards, the load-bearing capacity of the surface, the structure of the subsurface, and the regolith thickness;

(2) *Science Value*: Assess the composition of surface materials, the geologic context of the surface, the potential for geological activity, the proximity of near surface water, and the potential for active upwelling of ocean material.

To achieve these reconnaissance objectives, two additional notional payload elements are a Reconnaissance Camera (RC) and a Thermal Imager (ThI).

Conclusions: A Jupiter-orbiting spacecraft that makes many flybys of Europa would provide an excellent platform from which to conduct measurements to investigate Europa's ocean and ice shell, composition, and geology, and thus the potential ingredients for life. Most of the required measurements could be achieved through remote sensing techniques that tend to be resource-intensive, in terms of data volume and data rate drivers. Such needs would be readily accommodated through implementation of the Europa Clipper concept.

References: [1] Space Studies Board, (2011) The National Academies Press, Washington, DC. [2] Europa Study Team, (2012) JPL Internal Document D-71990.

ASTROBIOLOGICAL INVESTIGATION OF PITCH LAKE, TRINIDAD, AND ITS POTENTIAL AS AN ANALOG FOR TITAN.

J. N. Shivak[1] (jared.shivak@wsu.edu) and D. Schulze-Makuch[1], [1]School of the Environment, Washington State University, Pullman, WA.

Introduction: The study of extremophilic microorganisms able to tolerate extreme environmental conditions on the Earth (e.g., temperature, pressure, salinity, water activity, pH) has greatly expanded the range of environments currently considered as potential habitats for extraterrestrial microbial life. Extremophilic microbiota are considered to be the most likely candidates for successful extraterrestrial life elsewhere in the universe [5], [8].

NASA's Cassini mission has discovered abundant evidence of liquid hydrocarbon (methane-ethane) lakes on the surface of Saturn's moon Titan [3], [9]. Organic reactivity in hydrocarbon solvents is no less versatile than it is in water, and many enzymes derived from microorganisms are believed to catalyze reactions by having an active site that is hydrophobic [1], making it theoretically possible to catalyze microbial metabolic reactions in the near-absence of liquid water. This suggests that microbial metabolism in a hydrophobic, water-scarce environment such as the surficial hydrocarbon lakes of Titan is possible and may in fact be energetically favorable [4]. The liquid hydrocarbon lakes on the surface of Titan are therefore a potential habitat for microbial life.

Preliminary Work: Located in Trinidad and Tobago, Pitch Lake is a natural asphalt lake that is sourced from seepage of asphaltenes and other heavy hydrocarbons from the surrounding petroleum-rich host rocks [7]; it is the largest of three such reservoirs on the surface of the Earth. During upward seepage, pitch mixes with mud and gases under high pressure, and the lighter portion evaporates or is volatilized, which produces a liquid asphalt residue characterized by low water activity, recalcitrant carbon substrates, and noxious chemical compounds [2].

Despite the harsh conditions, an active extremophilic microbial community of archaea and bacteria was discovered to thrive in Pitch Lake [7]. This microbial community was found to be incredibly diverse, but the exact mechanisms being utilized by the microorganisms to metabolize and survive in the lake are poorly understood at present.

Pitch Lake as an Analog for Titan: We propose that despite several differences, Pitch Lake is one of the best terrestrial analogs to the surface of Titan currently available for study on the Earth and should be the subject of targeted astrobiological investigations. The two primary differences between Pitch Lake and the surface of Titan are temperature and hydrocarbon composition. Measured temperatures of Pitch Lake are significantly warmer than anticipated temperatures within the hydrocarbon lakes on Titan, even though some of the Titan's lakes may be heated from below [4], [6]. The hydrocarbon composition of Pitch Lake is poorly constrained, but contains asphaltenes and other long-chain hydrocarbons [7]. Modeling suggests that the lower levels of hydrocarbon lakes on Titan may contain heavy, more processed material [6]. However, the hydrocarbons in Pitch Lake are expected to be significantly heavier and more complex than within the methane-ethane reservoirs near the surface of Titan [6], [9]. The discovery of microbial communities thriving in Pitch Lake makes it one of the rare habitatson Earth where microorganisms are able to survive in a hydrocarbon-rich, hydrophobic environment. This makes Pitch Lake an ideal analog site to study the novel adaptations that have been developed by the microbiota in this unique environment; which will provide key insights into the possibilities for microbial life in the liquid hydrocarbon lakes on Titan.

References: [1] Benner S.A., Ricardo, A., Carrigan M.A. (2004) *Curr. Op. in Chem. Biol.* 8, 672–689. [2] Dia A.N., Castrec-Rouelle M., Boulegue, J., Comeau, P. (1999) *Geochim. Cosmochim. Ac.* 63 (7/8), 1023-1038. [3] Lorenz R.D., Mitchell K.L., et al. (2008) *GRL* 35. [4] McKay C.P. and Smith, H.D. (2005) *Icarus* 178, 274–276. [5] Schulze-Makuch D., Fairen A.G., Davila A.F. (2008) *IJA* 7 (2), 117-141. [6] Schulze-Makuch D. and Grinspoon D.H. (2005) *Astrobiology* 5, 560–567. [7] Schulze-Makuch D., Haque S., et al. (2011) *Astrobiology* 11 (3), 241-258. [8] Southam G., Rothschild L.J., Westall F., (2007) *Space Sci. Rev.* 129, 7-34. [9] Stofan E.R., Elachi C., Lunine J.I., Lorenz R.D., et al. (2007) *Nature* 445, 61– 64.

TWO GEOLOGIC CONSTRAINTS ON EUROPA'S ICE SHELL THICKNESS AND IMPLICATIONS FOR HABITABILITY.

Kelsi N. Singer[1], William B. McKinnon[1], Paul M. Schenk[2], [1]Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis, MO 63130 (ksinger@levee.wustl.edu, mckinnon@wustl.edu); [2]Lunar and Planetary Institute, Houston, TX 77058.

Introduction: Constraining the thickness of the ice shell on Europa and the geological processes occurring in it are central to understanding any communication between the surface and subsurface ocean, and also assessing the viability of future spacecraft mission technologies for investigating this potentially habitable world. Radiolytic products on the surface are considered a source of potential oxidants that might be helpful for creating chemical gradients for europan life. Thinner ice shells would seem to more easily facilitate this transport.

We present empirically derived ice shell thickness estimates from two types of features: 1) endogenic pits and 2) ring graben around large impact basins. Both planometric and topographic measurements are employed to characterize the features. These are then related to plausible formation mechanisms and associated implications about ice shell thickness are discussed.

1) Endogenic Pits: Here we focus on circular-to-subcircular features generally agreed to have been created by endogenic processes in Europa's ice shell or ocean: pits, uplifts, and subcircular chaos regions. We mapped all such features in the size range of 1 to 50 km in diameter in the ~200 m px^{-1} Galileo regional maps (~9% of Europa's surface), as well as over available high-resolution regions. Results of this mapping show decreasing numbers of small features, and a peak in the size distribution for all features at approximately 5–6 km in diameter [1]. No pits smaller than 3.3 km in diameter were found.

Topography was used to find the depths and heights of pits and uplifts in the mapped regions. A general trend of increasing pit depth with increasing pit size was found, a correlation more easily understood in the context of a diapiric hypothesis for feature formation (as opposed to purely non-diapiric, melt-through models) [1]. Based on isostasy, maximum pit depths of ~0.3-to-0.48 km imply a *minimum* shell thickness on Europa of ~3-to-8 km, depending on the composition of the ice and underlying ocean.

2) Impact Basin Graben: We analyzed ring graben surrounding the two largest multiring basins on Europa, Tyre (~38 km in diameter) and Callanish (~33 km). The radial extension necessary to form these graben is presumably caused by a combination of gravity sliding and asthenospheric drag of more ductile ice and/or water flowing towards the excavated center of the crater under a brittle lithospheric lid [e.g., 2,3].

Graben *widths* are used to estimate the intersection depth of the bounding normal faults, a quantity related to the brittle-ductile transition (BDT) depth that approximates the elastic shell thickness. Graben widths vary, with Tyre graben slightly larger (mean of 2.0 ± 0.8 compared with 1.4 ± 0.7 km for Callanish). The geometry is such that, with typical normal fault dips, the fault intersection depth is ~equal to the width of the graben. Classic models of graben formation predict the brittle-ductile transition (BDT) occurs at the fault intersection, and others predict the BDT could be at as much as twice the fault intersection depth [4-6]). Elastic shell thickness implied are 1.5–4 km.

Measurements of graben *depths* result in estimates of displacement, strain, and stress experienced by the ice shell (see methodology and results in [7]). Maximum radial strains are in the range of 0.5–1.5% (Tyre) and 0.3–1.1% (Callanish). Strain rates for a collapsing transient crater are on the order of the inverse gravitational free-fall time, but nominally decline with a r^{-4} radial dependence [2,8]. We find maximum strain rates on the order of 10^{-5}-to-10^{-6} s^{-1}. For BDT depths of 3–4 km, the implied heat flows for solid ice conductivities [9] are ~150–200 mW m^{-2}. Realistic (lower) conductivities could reduce these heat flows by half. At these strain rates, the temperatures at the BDT are relatively high. Simply extrapolating to the depth of melting, assuming a conductive as opposed to a convective temperature profile, results in estimates of 3.2–4.3 km total shell thicknesses. If the ring graben formed over longer time scales, thicker shells are indicated.

Discussion: Substantial ice shell thickness variations over time are plausible, and our conclusions regarding shell thickness strictly refer to the epoch of feature formation. Both feature analyses suggest an endmember minimum of an ~3 km ice shell. Although not common features, Europa's larger impacts and their associated ring faults clearly facilitate material communication between the surface and the ocean.

References: [1] Singer, K.N. et al. (2010) *LPS XLI* abs. #2195. [2] Melosh H.J. and McKinnon W.B. (1978) *GRL 5*, 985–988. [3] McKinnon W.B. and Melosh H.J. (1980) *Icarus 44*, 454–471. [4] Schultz R.A. et al. (2007) in *The Geology of Mars*, CUP, 371-399. [5] Bland M.T. et al. (2010) *Icarus 210*, 396-410. [6] Schultz-Ela D.D. and Walsh, P. (2002) *J. Struct. Geol. 24*, 247-275. [7] Singer, K.N. et al. (2013) *LPS XLIV*. abs. #2197. [8] Allemand P. and Thomas P.G. (1991) *JGR 96*, 20,981-20,988. [9] Petrenko V.F. and Whitworth R.W. (1999) *Physics of Ice*, OUP.

SOLUBILITY OF ORGANICS IN LIQUID HYDROCARBONS UNDER TITAN SURFACE CONDITIONS.

S. Singh[1], V. F. Chevrier[1], M. Leitner[1], M. Gainor[1], L. Roe[1], [1]Arkansas Center for Space and Planetary Sciences, University of Arkansas (Fayetteville, AR, 72701, USA; sxs099@uark.edu)

Introduction: Titan is the only body aside from Earth on which stable bodies of liquid have been found [1]. Its lakes contribute to a methane-driven hydrological cycle making it a good analog to an early Earth. The exact composition of its lakes however is still a subject of study. They are thought to be composed predominantly of methane and ethane as well as a variety of other hydrocarbons and hydrocarbon ices [2, 3]. However current results lack precision and the solubility of these various molecules under Titan conditions is not very well studied. Acetylene (C_2H_2) is thought to be major component dissolved in Titan lakes [2] and acetonitrile (CH_3CN) is of great interest due to its astro-biological implications and its role as a pre cursor in the formation of amino acids [4].

Experimental Setup: The experimental facility used for the experiments is specifically designed for simulating Titan surface condition [5]. Pressure of 1.5 bar is maintained with N_2 gas and temperature of 90 - 94 K is maintained with liquid nitrogen. Organics compounds are condensed from gas phase in the condenser, then washed with liquid hydrocarbons (methane or ethane) and collected in a Petri dish. The Titan chamber is also connected to a Nicolet 6700 FTIR that acquires *in situ* IR spectra of the sample via fiber optic. The sample mass is also continuously recorded to measure potential liquid, any variation in mass emphasize the presence or absence of these compounds during evaporation/sublimation processes [6].

Results: Fig. 1 shows the dissolution of C_2H_2 in pure methane and ethane. The main features for C_2H_2 are an absorption bands centered at 1.54 µm and a negative slope at 2.0 µm. These spectral features lie within the two largest VIMS atmospheric windows. Similar spectral features are observed in the mixture spectra of C_2H_2 with CH_4 and C_2H_6 (Fig.1). The band depth of C_2H_2 absorption bands in liquid methane is lower than the band depth of C_2H_2 abortions band in liquid ethane (Fig.1) indicating that C_2H_2 is more soluble in liquid ethane.

Fig. 2 shows the dissolution of CH_3CN in pure methane and ethane. Absorption band for CH3CN are centered at 1.14, 1.19, 1.37, 1.45, 1.59, 1.66, 1.85, 2.0 µm and negative slope at 2.05 µm (Fig. 2A). CH_3CN is near its saturation point in liquid ethane due to the flat C-H stretch centered at 1.66 µm (Fig. 2C) that is also a major feature in pure CH_3CN spectra (Fig. 2A). Only few CH_3CN absorption bands can be resolved in the mixture of CH_3CN and CH_4 indicating lower solubility in liquid methane.

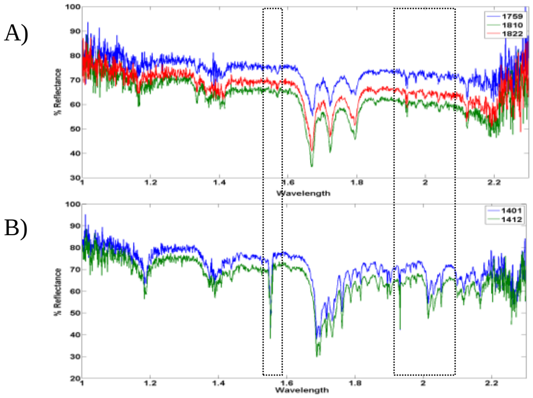


Figure 1: Acetylene in Liquid methane (A) and ethane (B)

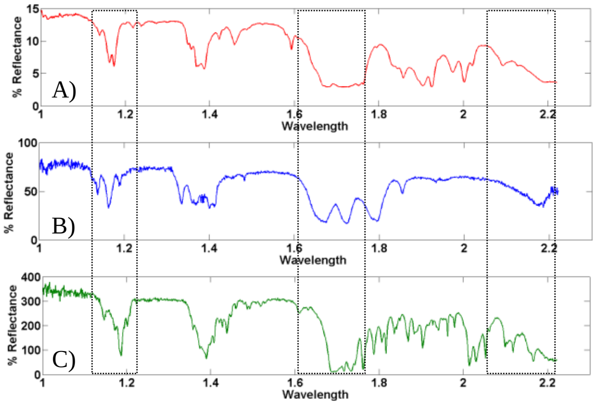


Figure 2: Pure acetonitrile (A) and dissolved in liquid methane (B) and ethane (C).

Conclusions: We have successfully conducted several different liquid-liquid and liquid–solid hydrocarbon experiments in our lab under Titan surface conditions. Our solubility spectra show that C_2H_2 and CH_3CN are far more soluble in liquid ethane than in liquid methane. To calculate the exact solubility values a spectra un-mixing model is being developed. The spectral features seen at 1.59 µm and 2.0 µm region lie within two of the VIMS atmospheric windows. The absorption features seen in laboratory spectra are large enough to be potentially detected in VIMS data.

Acknowledgements

This work is funded by NASA Grant project # NNX10AE10G.

References: [1] E.R. Stofan, et al. (2007) *Nature*, 445:61. [2] D. Cordier, et al. (2011) *PSS*, 3101. [3] G. Mitri, et al. (2007) *Icarus* 186, 385-394. [4] F. Raulin (2008) *Space Sci. Reviews* 135, 37-48. [5] F.C. Wasiak, et al. (2013) *ASR*, 51, 1213-1220. [6] A. Luspay-Kuti, et al. (2012) *GRL*, 39, L23203.

IN SITU PLASMA MEASUREMENTS AT THE GALILEAN MOONS EUROPA, GANYMEDE AND CALLISTO.

E. C. Sittler Jr.[1], J. F. Cooper[1], N. Paschalidis[1] and A. S. Lipatov[2], [1]NASA Goddard Space Flight Center, Greenbelt, MD, 20771, [2]University of Maryland Baltimore County/NASA Goddard Space Flight Center, Greenbelt, MD.

Introduction: We will present measurement requirements for plasma measurements made at the Galilean moons with plasma package composed of Ion Mass Spectrometer (IMS), Electron Spectrometer (ELS) and Energetic Particle Detector (EPD). This complement of instruments, as discussed in [1] for Europa, will provide measurements of plasma velocity moments including density, flow velocity and pressure which are important to measure the dynamics of the interaction between the moon and Jupiter's magnetosphere. The induced currents and their corresponding magnetic fields can be important corrections to the induced magnetic fields from sub-surface ocean measurements by magnetometer on spacecraft flying past the moon or in orbit about the moon.

Ion Composition and Electron Measurements: Kinetic effects such as pickup ion currents and field aligned polar outflows of ionospheric plasma will be revealed by species resolved ion velocity distribution function measurements and electron distribution function measurements. Composition measurements will allow one to measure the ion ram pressure ρV^2 and ion thermal pressures and their spatial gradients ∇P of the upstream Jovian magnetospheric flow that is impinging upon the moon and its exosphere. The IMS will measure the dynamic ram pressure term with energies ~ 1 keV, while the EPD will measure the pressure term dominated by hot plasma with ~ 100-200 keV temperatures [1]. In addition the composition measurements will be important for separating magnetospheric plasma flows (O^+/S^{++} and S^+) from pickup ion currents (O_2^+). Field aligned polar ion outflows, driven by field aligned electron pressure gradients, as reported in [1] for Europa will provide important composition information about the moon's lower ion exosphere from spacecraft altitudes which can be > 100 km. These outflows can also be an important sink for the ion exosphere [1] and must therefore be replenished. All the above combined information will feed back into our understanding of the interaction via hybrid simulations of the interaction. The hybrid simulations will then provide the needed corrections to magnetometer measurements of the moon's sub-surface ocean. Composition measurements will also provide important information about ion sources (i.e., exogenic versus endogenic sources) as discussed in [2] and the habitability of the moon's sub-surface ocean as thought to exist at Europa.

Conclusion: Such measurements will be important for such future missions to the Galilean moons such as Clipper and other future missions that may be under consideration. This presentation will trace the science requirements from another presentation of this workshop [2] and translate them into instrument requirements.

References:

[1] Sittler, E. C., Jr. et al., (2013), *Planet. Space Sci.,* in press. [2] Cooper, J. F. and E. C. Sittler, *The Habitability of Icy Worlds,* (2014), Abstract #4026.

CONVECTIVE PROCESSES IN EUROPA'S OCEAN AND THEIR IMPLICATIONS FOR ICE-OCEAN COUPLING.

Krista M. Soderlund[1], Britney E. Schmidt[2], Johannes Wicht[3], Donald D. Blankenship[1], [1]University of Texas at Austin, John A. and Katherine G. Jackson School of Geosciences, Institute for Geophysics (UTIG), J.J. Pickle Research Campus, Bldg. 196; 10100 Burnet Road (R2200), Austin TX 78758-4445, USA. (krista@ig.utexas.edu; blank@ig.utexas.edu). [2]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Drive, Atlanta, GA 30332-0340, USA (britneys@eas.gatech.edu). [3]Max Planck Institute for Solar System Research, 37191 Katlenburg-Lindau, Germany (wicht@mps.mpg.de).

Introduction: Jupiter's satellite Europa possesses a global liquid water ocean overlain by an ice shell that mediates heat flux from the deeper interior [1]. This sandwiching of the ocean between a potentially active silicate mantle and geologically dynamic ice shell makes Europa one of the most promising extraterrestrial habitats in the solar system. It is therefore critical to understand the ocean's dynamics and chemistry. Although no direct oceanographic measurements are presently available, geologic features observed on the surface may provide constraints on Europa's internal dynamics. In particular, regions of disrupted ice known as chaos terrain are thought to be linked to subsurface processes [2] and concurrence with ocean-derived salts at lower latitudes [3] implies a coupling between the ocean and ice shell.

Vigorous thermal convection is likely driven in the ocean by temperature differences between the hot silicate mantle and the cold ice shell. The resulting currents will reorganize the flow of heat from the mantle on both global and local spatial scales, potentially leading to spatial variations in heat exchange between the ocean and ice shell. Thus, the pattern of heat flow along the ice-ocean interface in global thermal convection models may be used to assess the potential for ocean-driven processes in the ice shell.

Ocean Convection Model: Guided by state-of-the-art rotating convection theory [4], our team has developed a novel hypothesis for Europa's ocean where the dynamics are less constrained by rotation than previously assumed [5]. We simulate three-dimensional, time-dependent convection of a Boussinesq fluid in a rotating spherical shell. Small-scale convection adopts a three-dimensional structure and is more vigorous at lower latitudes (Fig. 1**a**). Global-scale currents are organized into and two equatorial Hadley-like circulation cells (Fig. 1**b**) three zonal jets (Fig. 1**c**). Mean radial current speeds are ~3 cm/s and zonal (east-west) speeds are typically ~250 cm/s. These motions transmit the satellite's internal heat most effectively in the equatorial region (Fig. 2), which can directly influence the latitudinal thermo-compositional state and structure of the ice shell. This heterogeneity may promote the formation of chaos features through increased melting of the ice shell at low latitudes and subsequent deposition of marine ice.

This work implies that thermal gradients along the base of the ice shell due to underlying ocean circulations are important to consider for the formation of chaos terrain, the evolution of Europa's ice shell, and the rates of mixing between the surface and subsurface.

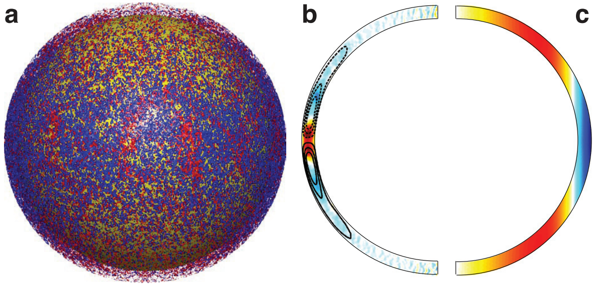


Figure 1: **a)** Instantaneous isosurfaces of axial vorticity in the bulk fluid. **b)** Time-averaged, axisymmetric radial velocity field with superimposed contours of the stream function where solid (dashed) contours indicate counterclockwise (clockwise) meridional circulations. **c)** Time-averaged, axisymmetric zonal flows where blue (red) indicates westward (eastward) motions.

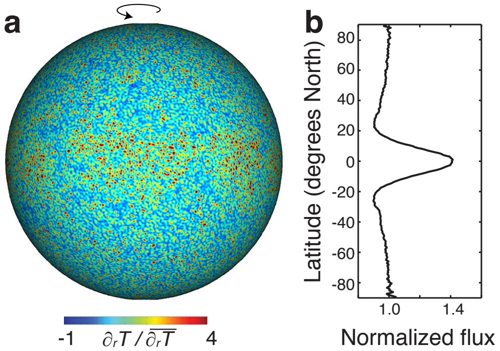


Figure 2: a) Instantaneous radial heat flux on the outer ocean boundary, normalized by the mean value. **b)** Time-averaged, axisymmetric radial heat flux as a function of latitude, normalized by the mean value.

References: [1] Khurana K.K. et al. (1998), *Nature 395,* 777-780. [2] Schmidt B.E. et al. (2011), *Nature* 479, 502-505. [3] Brown, M.E. & Hand, K.P. (2013), *Astron J.* 145, 110. [4] King, E.M. & Aurnou, J.M. (2013), *PNAS* 110, 6688-6693. [5] Soderlund, K.M. et al., (2013) *Nature Geosci*, doi:10.1038/ngeo2021**.**

HABITABILITY POTENTIAL OF ICY MOONS: A COMPARATIVE STUDY. A. Solomonidou[1,2], A. Coustenis[1], Th. Encrenaz[1], F. Sohl[3], H. Hussmann[3], G. Bampasidis[1,2], F. W. Wagner[3], F. Raulin[4], D. Schulze-Makuch[5], and R. M. C. Lopes[6], [1]LESIA - Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot –Meudon, France (anezina.solomonidou@obspm.fr), [2]National and Kapodistrian University of Athens, Department of Physics, Athens, Greece, [3]DLR, Institute of Planetary Research, Berlin, Germany, [4]LISA-IPSL, CNRS/UPEC & Univ. Paris Diderot, Créteil, France, [5]Washington State University, School of Earth and Environmental Sciences, Washington, USA, [6]Jet Propulsion Laboratory, Pasadena, California, USA.

Introduction: Looking for habitable conditions in the outer solar system our research focuses on the natural satellites rather than the planets themselves. Indeed, the habitable zone as traditionally defined may be larger than originally conceived. The strong gravitational pull caused by the giant planets may produce enough energy to sufficiently heat the interiors of orbiting icy moons. The outer solar system satellites then provide a conceptual basis within which new theories for understanding habitability can be constructed. Measurements from the ground but also by the Voyager, Galileo and the Cassini spacecrafts revealed the potential of these satellites in this context, and our understanding of habitability in the solar system and beyond can be greatly enhanced by investigating several of these bodies together [1]. Their environments seem to satisfy many of the “classical” criteria for habitability (liquid water, energy sources to sustain metabolism and chemical compounds that can be used as nutrients over a period of time long enough to allow the development of life).

Satellites of the gaseous giants : Indeed, several of the moons show promising conditions for habitability and the development and/or maintenance of life. Europa, Callisto and Ganymede may be hiding, under their icy crust, putative undersurface liquid water oceans [3] which, in the case of Europa [2], may be in direct contact with a silicate mantle floor and kept warm by tidally generated heat [4]. Titan and Enceladus, Saturn’s satellites, were found by the Cassini-Huygens mission to possess active organic chemistries with seasonal variations, unique geological features and possibly internal liquid water oceans. Titan’s rigid crust and the probable existence of a subsurface ocean create an analogy with terrestrial-type plate tectonics, at least surficial [5], while Enceladus’ plumes find an analogue in geysers. As revealed by Cassini the liquid hydrocarbon lakes [6] distributed mainly at polar latitudes on Titan are ideal isolated environments to look for biomarkers. Currently, for Titan and Enceladus, geophysical models try to explain the possible existence of an oceanic layer that decouples the mantle from the icy crust. If the silicate mantles of Europa and Ganymede and the liquid sources of Titan and Enceladus are geologically active as on Earth, giving rise to the equivalent of hydrothermal systems, the simultaneous presence of water, geodynamic interactions, chemical energy sources and a diversity of key chemical elements may fulfill the basic conditions for habitability.

Titan has been suggested to be a possible cryovolcanic world due to the presence of local complex volcanic-like geomorphology and the indications of surface albedo changes with time [7,8]. Such dynamic activity that would most probably include tidal heating, possible internal convection, and ice tectonics, is believed to be a pre-requisite of a habitable planetary body as it allows the recycling of minerals and potential nutrients and provides localized energy sources. In a recent study by Sohl et al. [2013], we have shown that tidal forces are a constant and significant source of internal deformation on Titan and the interior liquid water ocean can be relatively warm for reasonable amounts of ammonia concentrations, thus completing the set of parameters needed for a truly habitable planetary body.

Such habitability indications from bodies at distances of 10 AU, are essential discoveries brought to us by space exploration and which have recently revolutionized our perception of habitability in the solar system.

In the solar system’s neighborhood, such potential habitats can only be investigated with appropriate designed space missions, like JUICE-Laplace (JUpiter ICy moon Explorer) for Ganymede and Europa [9]. JUICE is an ESA mission to Jupiter and its icy moons, recently selected to launch in 2022.

References:

[1] Coustenis, A., Encrenaz, Th., in “Life Beyond Earth : the search for habitable worlds in the Universe”, Cambridge Univ. Press, 2013. [2] Patterson, G.W., et al.: AGU P41F-09, 2011. [3] Grasset, O., et al.: Astrobiology 13, 991-1004, 2013. [4] Sohl, F., et al.: submitted. [5] Solomonidou, A., et al.: PSS 77, 104-117, 2013. [6] Stofan, E.R., et al.: Nature 445, 61-64, 2007. [7] Solomonidou, A., et al.: submitted (a). [8] Solomonidou, A., et al: submitted (b). [9] Grasset, O., et al.: PSS, 78, 1-21, 2013.

FORMATION AND EVOLUTION OF TITAN'S ORGANIC SEAS. C. Sotin[1], K.J. Lawrence[1], B. Seignovert[1], J. W. Barnes[2], R.H. Brown[3], K.H. Baines[1], B.J. Buratti[1], R.N. Clark[4], and P.D. Nicholson[5]; [1]Jet Propulsion Laboratory - Caltech, 4800 Oak Grove Drive, Pasadena, CA, 91109; [2]University of Idaho, Engineering-Physics Building, Moscow, ID 83844; [3]University of Arizona, Lunar and Planetary Laboratory, 1629 E. University Blvd., Tucson, AZ 85721; [4]United States Geological Survey, Mail Stop 964, Box 25046, Denver Federal Center, Denver, CO 80225; [5]Cornell University, 418 Space Sciences Building, Ithaca, NY 14853.

Introduction: Titan, Saturn's largest moon, is the only object in the Solar System, besides Earth, to support stable bodies of liquids at its surface. It is also the only moon with a dense atmosphere. Among the ingredients that are put forward to define habitability. Titan's seas are made of ethane [1] and more likely methane which is abundant in its atmosphere. The global carbon cycle [2] includes the formation of complex organic molecules that form Titan's haze. One key aspect of the cycle is that the present amount of atmospheric methane would be consumed in a short geological time (a few tens of million years) in the absence of a replenishment mechanism.

This study describes observations of the northern seas by the Visual and Infrared Mapping Spectrometer (VIMS) onboard the Cassini spacecraft. It compares images that were taken just after equinox with more recent images for investigating processes involved in the evolution of Titan's organic seas.

Observations of the seas: Titan's northern polar area is covered by three large seas named Punga Mare, Ligeia Mare, and Kraken mare [3]. These seas are very dark on radar images, dark on optical images and very reflective when observed in the specular reflection geometry [4]. Using the recently released topographic map [5] and the order 4 Titan geoid [6], one can observe that the northern seas are located in the deepest topographic lows, about 1 km below the reference equipotential surface. However, such liquid bodies have not been observed in similarly deep depressions in the southern hemisphere. The Cassini mission offers opportunity to observe the evolution of both hemispheres at different seasons in order to investigate whether this difference is seasonal.

Another observation is that these seas are very often bordered by terrains that are very bright at 2 µm and at 5 µm (Fig. 1). They are also characterized by a very small value of the 2.70 µm/2.78 µm ratio which is an indication of very low amount of water ice although the interpretation of this ratio for Titan is still being investigated. These bright deposits could be organic deposits left over as seas evaporated in the past [7].

Evolution of the seas: Observations taken between 2010 and 2013 show that the shores of the northern seas have not changed. This observation suggests that little evaporation if any has occurred. More observations will become available during the Cassini Solstice mission and variations may be observed since the amount of sunlight getting to the surface increases during spring. Observations of the southern pole are equally important if one wants to witness possible refilling of the large depressions by rainfalls.

The relationships between the bright deposits, the lakes, and the seas are being investigated and will be reported. Observing the evolution of Titan's organic seas is key to our understanding of the formation of organics in the solar system, a key ingredient for habitability.

References: [1] Brown, R.H. et al. (2008) *Nature 454, 607–610*. [2] Sotin C. et al. (2012) Icarus, 221, 768-786. [3] Stofan, E.R. et al. (2007) Nature 445, 61–64. [4] Barnes, J.W. et a. (2013) ApJ, 777:161. [5] Lorenz R.D. et al. (2013) Icarus 225, 367-377 [6] Iess L. et al. (2012) Science 337, 457-459. [7] Barnes J.W. et al. (2011) Icarus, 216, 136-140.

.

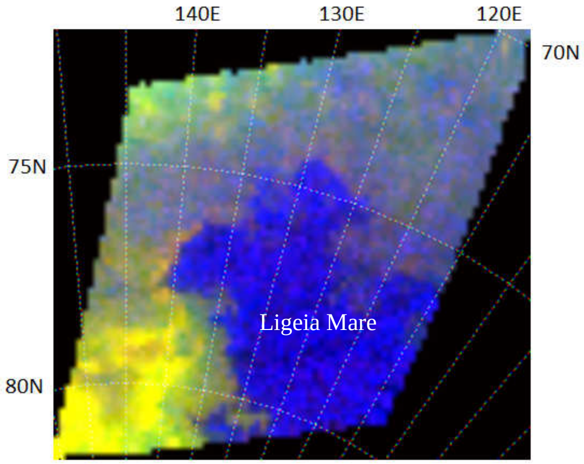


Figure 1: False color image of Titan's northern pole taken by the VIMS instrument on September 12, 2013. The colors have been set to outline the sea (dark blue) and the evaporite candidates (bright yellow)

Acknowledgments: This work has been performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. It was partly funded by NASA Astrobiology Institute.

.

SURFACE DUST MASS ANALYZER FOR THE COMPOSITIONAL MAPPING OF ICY SURFACES.

Z. Sternovsky[1,2], S. Kempf[1], E. Grün[1], M. Horányi[1], R. Srama[3], [1] LASP, Univ. of Colorado Boulder, CO, USA, [2] Aerospace Eng. Sciences, Univ of Colorado, Boulder, CO, USA, [3] IRS, Universität Stuttgart, Germany. (1234 Innovation Drv., Boulder, CO, 80303, Zoltan.Sternovsky@colorado.edu).

Introduction: A low-mass, low-power and high performance surface dust analyzer is under development for the application of upcoming mission of exploring the habitability of icy worlds. The SUrface Dust Analyze (SUDA, Fig. 1) is a reflectron-type dust analyzer instrument that is capable of measuring the chemical and elemental compositions of impacting dust particles with a mass resolution of $m/\Delta m \approx 200$ and mass range 1-500 u. The SUDA instrument will be used to measure the composition of ballistic dust particles ejected from the surfaces of icy moons by impacting micrometeoroids. The ejecta cloud is permanently present due to the continual bombardment and has been detected and characterized by the Galileo spacecraft around all of the Jovian icy moons [1]. The SUDA instrument thus can map the composition of the surface from orbit. The majority of the detected particles have a speed that is small compared to that of the spacecraft and thus the ejecta particles are detected in the apex direction. SUDA also measures the speed of the impacting particles that allows calculating the location of origin on the surface with an accurate that is considerably smaller than the altitude of the craft at the time of detection. The laboratory version of the SUDA instrument has been tested and characterized (Fig. 2). Currently, the instrument is undergoing optimization for the operation in Jupiter's demanding environment.

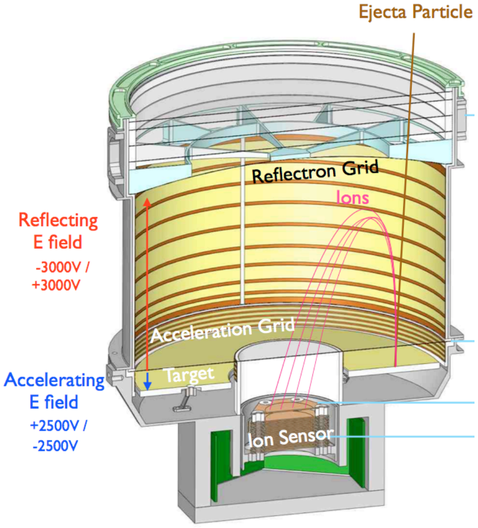


Fig. 1. The schematics of the SUDA instrument operation principle.

SUDA instrument: The dust impact occurs on the target surface placed near the bottom of the instrument. The ions generated in the impact are characteristic to the composition of the dust particles. The surface analysis method enabled by SUDA is in particular sensitive to the small contaminants that are preferentially ionized in the impact as it has been demonstrated by a similar instrument analyzing Enceladus's plumes [3]. Compared to previous instrument, SUDA achieves a significantly higher mass resolution power based on a novel ion optics design [e.g., 2] that focuses the impact-generated ions onto a centrally located detector for their time-of-flight measurements. SUDA can operate either in the positive/negative ion collection mode, which enhances correlation between the measured spectra and the composition of the moon's surface. The ion detector is specially designed for high sensitivity and high dynamic range allowing the detection of very minor constituents of the impact plasma cloud. The detector has a limited view of the space through the aperture of the instrument, however is shielded from the sides for reduced noise. Currently, the architecture of the electronic components as well as the mechanical design are under optimization to develop a low-power and low-mass version for near-future space application. The presentation will be a snapshot of the current state of development and characterization of the expected performance.

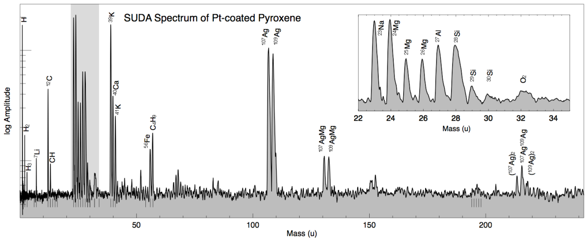


Fig. 2. A sample mass spectrum obtained by the SUDA instrument in the laboratory using a dust accelerator facility. SUDA achieves high mass resolution and high sensitivity.

References: [1] H. Krüger et al., Nature, 399 (1999). [2] Z. Sternovsky et al., Rev Sci Instrum, 78, 014501 (2007). [3] F. Postberg et al. Nature, 459, 1098–1101 (2009).

FT-IR measurements of cold cross sections of hydrocarbons

Keeyoon Sung[1], Geoffrey C. Toon[1], Linda R. Brown[1]
[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, U.S.A.
(ksung@jpl.nasa.gov; Geoffrey.C.Toon@jpl.nasa.gov; Linda.R.Brown@jpl.nasa.gov)

Introduction: Titan's stratosphere is abundant in hydrocarbons (C_xH_y) which produce highly complicated and crowded features in the spectra of **Cassini/CIRS**. The C_xH_y are either terminal or intermediate products from CH_4 photoloysis followed by subsequent atmospheric chemical reactions over geological time. Their spectroscopic observations reveal physical and chemical processes in the atmosphere, sheding light on our understanding of the formation and evolution of Titan. Therefore, high precision laboratory spectroscopy is demanded for the accurate interpretation of the spectroscopic observations, including identification of new molecules, whose absorption often overlaps.

Unfortunately, obtaining *complete and reliable* spectroscopic line parameters of polyatomic hydrocarbons using quantum-mechanics is impractical because their low-lying vibration and torsion states induce numerous hot bands while multiple vibrational interactions make conventional Hamiltonian modeling intractable. Instead empirical cross section are measured directly using high-resolution Fourier transform spectrometers. The temperature dependence can be obtained by using coolable absorption gas cells at the temperatures relevant to planetary atmospheres. Furthermore, we can use a new scheme of characterizing the measured crsoss sections to derive pseudo-line parameters (PLL) by fitting all the laboratory spectra simultaneously. The pseudoline parameters consist of line position, line strength, and lower state energy each line entry, by which one can effectively reproduce the measured cross sections. Results for several species is available from a website (managed by Geoffrey Toon at JPL (http://mark4sun.jpl.nasa.gov/data/spec/Pseudo).

One example is our recent study of mid-infrared (7 – 15 µm) propane (C_3H_8) at temperatures from 145 K to 297 K [1]. In total, 34 sets of pure and N_2-broadened spectra were measured at pressures from 3 Torr to 742 Torr using a Bruker IFS125 FT-IR at JPL and a 20.4 cm path long gas cell cooled by a closed-cycle helium refrigerator [2, 3]. The cross sections were measured and compiled for individual spectra recorded at various experimental conditions covering the planetary atmosphere and Titan. In addition, a propane pseudoline list (PLL) was generated with a frequency grid of 0.005 cm^{-1} by fitting the 34 laboratory spectra; line intensities and lower state energies were retrieved for each of the individual lines to reproduce the observed spectrum very well at both cold and room temperatures (See **Fig.1**). The total intensity in the 690 – 1550 cm^{-1} region was determined to be 52.93 (± 3 %)$\times10^{-19}$ cm^{-1} /(molecule·cm^{-2}) at 296 K by summing up the pseudoline intensities. This propane pseudolines were used to detect propylene (*alias* propene, C_3H_4) for the first time in Titan atmosphere by Cassini/CIRS [5] by characterizing major interfering features beloing to propane in the vicinity of the propylene band at 912 cm^{-1}. With this approach, study of benzene (C_6H_6) is underway, and three more C_3H_y hydrocarbons are proposed.

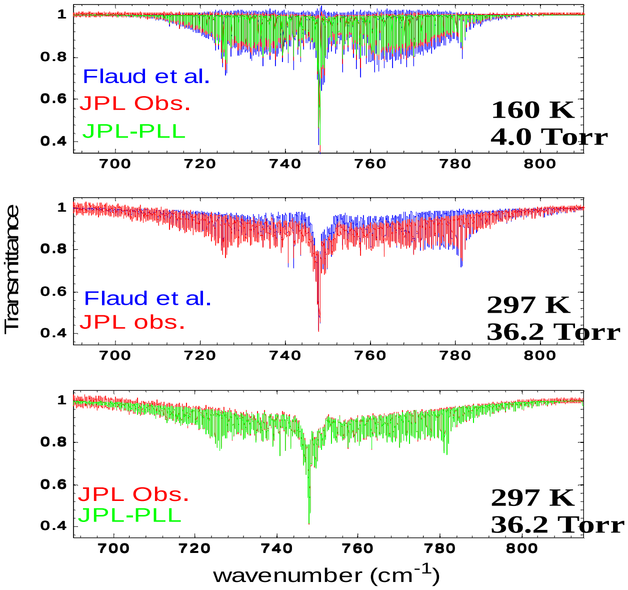


Fig. 1 Comparison of spectral fits to an observed lab spectrum. Top Panel: calculated using a true spectroscopic line prediction [4] for ν_{26} and a few hot bands. Bottom Panel: calculated, by pseudoline list. The results show that the PLL data set reproduces even the weak observed hot band features.

References:

[1] K. Sung et al. Icarus, 226, 1499-1513 (2013). [2] A.W. Mantz, et al. 65th Int'l symp. on Mol. Spectrosc., OSU at Columbus, Jun., 2010 [3] K. Sung, A. W. Mantz, M. A. H. Smith, et al., J Mol Spectrosc 262, 122, 2010. [4] J. M. Flaud et al., Mol Phys 108, 699, 2010. [5] C. A. Nixon et al. ApJL, 776, L14, 2013.

Acknowledgement: Research described in this paper was performed at the Jet Propulsion Laboratory, and California Institute of Technology, under contracts and cooperative agreements with the National Aeronautics and Space Administration.

Prebiotic Chemistry on Cryogenic Worlds: Tribochemical Reactions of Organics and Water in Titan Dunes.

Daniel A. Thomas and J.L. Beauchamp, Department of Chemistry, California Institute of Technology, Pasadena, CA 91125, dathomas@caltech.edu

Introduction: Titan's nitrogen-methane atmosphere provides the starting material for a wide array of organic compounds to be formed via photochemistry, and the presence of unsaturated hydrocarbon, amine, and polycyclic aromatic species has been supported by data from the Cassini-Huygens mission [1,2]. Production of organic compounds by UV irradiation of a simulated Titan atmospheric environment has yielded products that match the observed optical properties of Titan haze, suggesting that these compounds provide suitable analogs to Titan aerosol compounds [3, 4, 5].

Organics produced in Titan's atmosphere eventually settle to the surface, in part as condensed aerosols, and very likely contribute to the particulate matter comprising the expansive longitudinal dune features observed at mid-latitudes [6]. The chemical evolution of these vast stores of organic material is of great interest, as conditions that lead to incorporation of oxygen via contact with water ice or liquid water in Titan's low temperature environment may produce prebiotic molecules such as amino acids [7, 8].While the exact composition of the dunes of Titan is unknown, it is likely that they mainly comprise organic and water ice particles a few tenths of a mm in diameter, the ideal size for saltation by the winds of Titan [6]. In this work, we postulate that the mechanical energy imparted to wind-driven grains during the saltation process may drive chemical processes via the charging of particles due to friction (i.e. tribochemistry), leading in turn to formation of ions and free radicals in localized electrical discharges at particle interfaces [9].

Experimental Approach: Terrestial saltation processes have been measured to create electric fields up to 160 kV/m [10], well above the fields required to generate electrical discharges even at the higher pressures of Titan's surface. While the implications of such discharge events for the dust storms of Mars have been extensively studied, the results of such chemistry occurring on the surface of Titan are still wholly unknown.

To investigate such chemical processes, a system has been constructed to simulate the agitation that particles may experience during saltation on Titan's surface. As shown schematically in figure 1a, a flow of nitrogen gas cooled by passing through a coil submerged in liquid N_2 is employed to agitate a bed of particles between 250 µm and 1 mm in diameter that have been coated with a thin film of an organic compound of interest. The device is shown in operation in figure 1b. Once the system is cooled, a small amount of liquid water may be added to the system to provide a water-ice source for oxygen incorporation. After a short period of agitation the beads become highly charged, and exhibit increased adhesion to each other and to the glass apparatus. This charging effect can be enhanced by using a combination of borosilicate and polystyrene beads of various diameters.

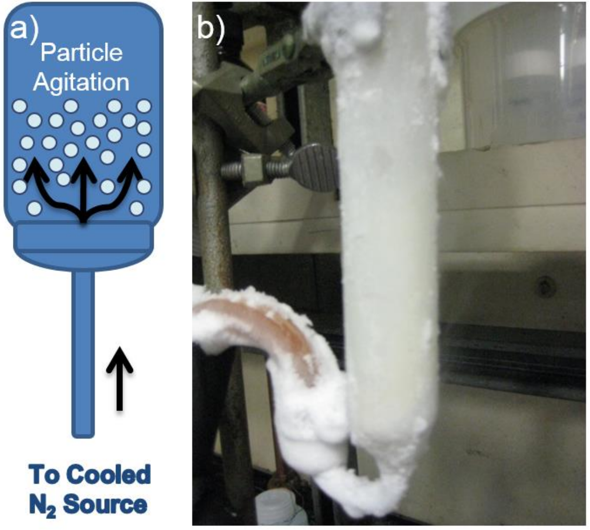


Figure 1. Experimental setup for simulating Titan dune chemistry; (a) Schematic representation of agitation of beads in fluidized bed; (b) current generation fluidized bed reactor in use (insulation removed for photo).

Following agitation, the beads are removed and rinsed with organic solvent, which is then analyzed via electrospray ionization mass spectrometry (ESI-MS). Initial experiments utilizing aminoacetonitrile as a precursor and room temperature nitrogen gas for agitation suggest the production of glycine during the course of the experiment. Improved extraction and analysis protocols are being investigated to verify these preliminary results. In addition, an enclosed device that will allow recycling of gases within the agitator to reduce the loss of semi-volatile products is also being explored.

References: [1] Coates, A. J., et al. (2009), *Planet. Space Sci.*, 57, 1866-1871. [2] Crary, F. J., et al. (2009), *Planet. Space Sci.*, 57, 1847-1856. [3] Khare, B. N., et al. (1984), *Icarus*, 60, 127-137. [4] Ramirez, S. I., et al. (2002), *Icarus*, 156, 515-529. [5] Imanaka, H., and M. A. Smith (2010), *PNAS*, 107, 12423-12428. [6] Lorenz, R. D., et al. (2006), *Science*, 312, 724-727. [7] O'Brien, D. P., R. D. Lorenz, and J. I. Lunine (2005), *Icarus*, 173, 243-253. [8] Neish, C. D., et al. (2010), *Astrobiology*, 10, 337-347. [9] Kajdas, C., and K. Hiratsuka (2009), *Proc. Inst. Mech. Eng.*, *Part J*, 223, 827-848. [10] D. S. Schmidt, et al. *JGR*, 103, 8997 (1998).

JUICE: THE ESA MISSION TO STUDY HABITABILITY OF THE JOVIAN ICY MOONS.

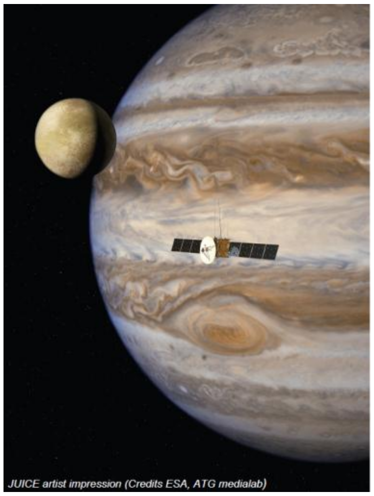
D. Titov[1], S. Barabash[2], L. Bruzzone[3], M. Dougherty[4], L. Duvet[1] , C. Erd[1] , L. Fletcher[5], R. Gladstone[6], O. Grasset[7], L. Gurvits[8,9], P. Hartogh[10], H. Hussmann[11], L. Iess[12], R. Jaumann[11], Y. Langevin[13] , P. Palumbo[14], G. Piccioni[15] and J.-E. Wahlund[16].
[1]ESA/ESTEC, The Netherlands, Dmitri.Titov@esa.int, [2]Swedish Institute for Space Physics, Sweden, [3]University of Trento, Italy, [4]Imperial College, London, UK, [5]University of Oxford, UK, [6]Southwest Research Institute, San Antonio, TX, USA, [7]University of Nantes, France, [8]JIVE, The Netherlands, [9]Delft University of Technology, The Netherlands, [10]Max Planck Institute for Solar System Research, Germany, [11]Institute of Planetary Research, DLR, Berlin, Germany, [12]Sapienza Università di Roma, Italy, [13]IAS, Orsay, France, [14]Università Parthenope - Napoli, Italy, [15]IAPS, Roma, Italy, [16]IRF-Uppsala, Sweden.

JUICE (JUpiter ICy moons Explorer) is the first L-class mission of the ESA's Cosmic Vision programme 2015-2025 [1, 2]. JUICE will perform detailed investigations of Jupiter and its system with particular emphasis on Ganymede as a planetary body and potential habitat. Investigations of Europa and Callisto will complete a comparative picture of the Galilean moons.

The overarching theme for JUICE is: *The emergence of habitable worlds around gas giants*. At Ganymede, the mission will characterize in detail the ocean layers; provide topographical, geological and compositional mapping of the surface; study the physical properties of the icy crusts; characterize the internal mass distribution, investigate the exosphere; study Ganymede's intrinsic magnetic field and its interactions with the Jovian magnetosphere. For Europa, the focus will be on the non-ice chemistry, understanding the formation of surface features and subsurface sounding of the icy crust over recently active regions. Callisto will be explored as a witness of the early solar system.

JUICE will perform a multidisciplinary investigation of the Jupiter system as an archetype for gas giants. The circulation, meteorology, chemistry and structure of the Jovian atmosphere will be studied from the cloud tops to the thermosphere. The focus in Jupiter's magnetosphere will include an investigation of the three dimensional properties of the magnetodisc and in-depth study of the coupling processes within the magnetosphere, ionosphere and thermosphere. Aurora and radio emissions will be elucidated. JUICE will study the moons' interactions with the magnetosphere, gravitational coupling and long-term tidal evolution of the Galilean satellites.

JUICE will be a three-axis stabilised spacecraft with dry mass of about 1800 kg at launch, chemical propulsion system and 60-75 m^2 solar arrays. The high-gain antenna of about 3 m in diameter will provide a downlink capability of not less than 1.4 Gb/day. The launch is foreseen is June 2022. After the Jupiter orbit insertion in January 2030, the spacecraft will perform a 2.5 years tour in the Jovian system investigating the atmosphere and magnetosphere of the giant. Gravity assists at Callisto will shape the trajectory to perform two targeted Europa flybys and raise the orbit inclination up to 30 degrees. 13 Callisto flybys will enable unique remote observations of the moon and *in situ* measurements in its vicinity. The mission will culminate in a dedicated 8 months orbital tour around Ganymede that will include high (5000 km), medium (500 km), and low (200 km) circular orbits.


JUICE artist impression (Credits ESA, ATG medialab)

The JUICE spacecraft will carry highly capable scientific payload consisting of 10 state-of-the-art instruments onboard the spacecraft plus one experiment that uses the spacecraft telecommunication system with ground-based telescopes. The *remote sensing package* includes a high-resolution multi-band visible imager (JANUS) and spectro-imaging capabilities from the ultraviolet to the sub-millimetre wavelengths (MAJIS, UVS, SWI). A *geophysical package* consists of a laser altimeter (GALA) and a radar sounder (RIME) for exploring the surface and subsurface of the moons, and a radio science experiment (3GM) to probe the atmospheres of Jupiter and its satellites and to perform measurements of the gravity fields. An *in situ package* comprises a powerful particle environment package (PEP), a magnetometer (J-MAG) and a radio and plasma wave instrument (RPWI), including electric fields sensors and a Langmuir probe. An experiment (PRIDE) using ground-based Very-Long-Baseline Interferometry (VLBI) will provide precise determination of the moons ephemerides.

The presentation will give an overview of the JUICE mission, its science scenario, observation strategy, and the newly selected payload.

TIDAL AND ROTATIONAL SIGNATURES OF INTERNAL OCEANS ON TITAN, GANYMEDE AND CALLISTO

G. Tobie[1], R.-M. Baland[1], O. Bollengier[1], A. Lefevre[1], G. Mitri[2,3]. [1]Université de Nantes, CNRS, Laboratoire de Planétologie et Géodynamique de Nantes, UMR-6112, 44322 Nantes, France ; [2]Istituto di Astrofisica e Planetogia Spaziali, Instituto Nazionale di Astrofisica, 00133 Roma, Italy, [3]Lunar and Planetary Laboratory, University of Arizona, USA ; (gabriel.tobie@univ-nantes.fr).

The magnetic data returned by the Galileo spacecraft have suggested that deep salty water oceans are present within Europa, Ganymede and Callisto [1,2]. As these three icy moons are subjected to significant tidal deformation, the presence of an internal ocean on these three icy moons is predicted to result in a significant deflection of both their surface and internal mass redistribution [3,4,5,6,7]. Gravimetric and altimetric measurements to be performed by the ESA JUpiter ICy moon Explorer (JUICE) mission [8] should be able to confirm the presence of the internal oceans by monitoring the periodic surface deflection and gravity change on Ganymede, and on Callisto by monitoring the gravity fluctuations. We will first discuss recent results on the tidal deformation and obliquity of Titan, and using the same model we will present the predicted tidal deformation for Ganymede and Callisto to be tested by the future ESA's JUICE mission.

Time-varying gravity fluctuations due to tides have been recently detected on Titan by the Cassini spacecraft [9], providing strong evidence for the existence of an internal water ocean (possibly salted) several tens of kilometers below the surface [10,11]. By solving the equations of motion for a compressible viscoelastic layered interior subjected to time-varying potential [e.g.7], we recently showed that the tidal response of Titan (tidal Love number k_2) is very sensitive to the density profile throughout the internal ocean and to a lesser extent to the ice shell properties (thickness, shear modulus, density) [10,11]. We showed that a wide variety of internal structure models can explain the inferred tidal Love number [11]. However, by considering additional constraints such as non-zero obliquity, degree-two static gravity field and surface shape, we showed that the number of admissible interior models becomes very small. By considering all these observational constraints, our analysis indicated that the thickness of Titan's outer ice shell is at least 40 km and the ocean thickness is less than 100 km, with an averaged density of $1300 - 1350$ kg m^{-3} [11].

In preparation of the future measurements to be performed by the JUICE mission, we perform similar computations for Ganymede and Callisto to determine how sensitive the tidal response and obliquity solutions are to the the size and location of the liquid layers, and its density profile. As for Titan, we adopt for Ganymede and Callisto an internal structure with an outer ice I shell, a subsurface ocean overlying a high pressure ice layer with phases III, V, and VI, and a rocky deep interior. We also consider that Callisto should be in a partially differentiated state. It has been recently proposed that, owing to the high density of aqueous $MgSO_4$ solutions (a likely aqueous candidate on Ganymede), liquid layers may be present not only below the outer ice I layer but also possibly at the ice VI-rock interface, or between overlying layers of ice VI–V or V–III [12]. To test this possibility, we consider different possible concentrations in $MgSO_4$ and we determine the possible size and location of the liquid layer within the whole H_2O mantle using experimental data on phase equilibria [13]. First sensitivity tests and comparison with expected JUICE/3GM accuracies will be presented.

References: [1] Khurana, K. K. et al. *Nature*, 397, 777–780 (1998). [2] Kivelson, M. G. et al. *Icarus,* 157, 507–522, (2002). [3] Castillo, J. et al. *C.R. Acad. Sci.,* 330, 659–666, (2000). [4] Moore, W. B., and G. Schubert, *Icarus*, 147, 317–319, (2000). [5] Moore, W. B., and G. Schubert, *Icarus,* 166, 223-226, (2003). [6] Wahr J. et al. *J. Geophys. Res.*, 111, E12005 (2006). [7] Tobie G. et al. *Icarus,* 177, 534–549 (2005). [8] Grasset, O. et al. *PSS* 78, 1-21 (2013). [9] Iess et al. *Science*, (2012). [10] Mitri et al. *Icarus*, in rev. [11] Baland et al. *Icarus,* in rev. [12] Vance S. and Brown , J. M. Geochim. Cosmochim. Acta 110, 176-189 (2013). [13] Bollengier O. et al., *this workshop.*

Acknowledgements: The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013 Grant Agreement no. 259285), and from the Region Pays de la Loire (France).

FORMATION AND EVOLUTION OF AN INTERNAL WATER OCEAN ON TITAN.

G. Tobie[1], O. Bollengier[1], A. Lefevre[1], N. Marounina[1], J. Monteux[1], R.-M. Baland[1], L. Bezacier[2], H. Amit[1], S. Carpy[1], G. Choblet[1], and O. Grasset[1]. [1]Université de Nantes, CNRS, Laboratoire de Planétologie et Géodynamique de Nantes, UMR-6112, 44322 Nantes, France; [2]European Synchrotron Radiation Facility, 38000 Grenoble, France; (gabriel.tobie@univ-nantes.fr).

For many years, a variety of theoretical models have predicted the presence of a liquid water ocean inside Titan. Several lines of evidences (tides [1], rotation [2,3], electric field perturbations [4]) now confirm that Titan harbors a water ocean (possibly salt-rich [2,5]) underneath an outer icy shell several tens to more than hundred kilometers thick. Analyses of the gravity and long-wavelength topography data indicate that the thickness of the ice shell is estimated to vary by about 5 km, which may be the consequence of heterogeneous ocean crystallization processes [5,6,7,8]. Moreover, the detection of a significant amount of ^{40}Ar (the decay product of ^{40}K) in Titan's atmosphere ([9]) indicates that leaching processes permitted the extraction of a significant amount of potassium from the rocky core to the ocean ([10]), followed by the outgassing of ^{40}Ar through the outer ice shell [11].

Despite the major advances provided by the Cassin-Huygens mission, the physical and chemical characteristics of the present-day internal ocean remain uncertain as well as its past evolution. The ocean probably played a crucial role in the formation of the primitive atmosphere as well as in the chemical exchanges between the inner part and the atmosphere all along Titan's evolution. In order to address the conditions under which the ocean formed and evolved throughout Titan's history, we combine different numerical and experimental approaches.

To constrain the ice melting during the accretion stage and the formation of a surficial ocean, we developed a new 3D numerical model which simulates the cumulative effect of large impacts ([12]). Our simulations show that the formation of a surficial ocean may start very early during the accretion stage, when the radius of the growing moon exceeds only 1200-1500 km. At the end of the accretion, the liquid water on Titan may constitute up to 30-35% of the total mass and should be in equilibrium with a very massive atmosphere [11]. In order to determine the post-accretional cooling and crystallization of the primordial ocean, we are currently developping a model describing the coupled thermo-chemical evolution of the ocean-atmosphere system.

Once separated from the atmosphere by the solidification of a primordial crust, the evolution of the ocean is mostly controlled by heat and mass transfers with the inner core and throughout the outer icy shell. To constrain the chemical evolution during the differentiation of the inner proto-core and the ocean crystallization, we conducted a series of experimental investigations at high pressure with particular focuses on two water-gas systems: H_2O-CO_2 ([13]) and H_2O-CH_4 ([14]), which are the dominant carbon species in Titan's interior ([15]). Based on these new experimental results, we are developing a thermodynamical model which will allow us to compute the time evolution of CH_4 and CO_2 content in the ocean during crystallization and the exchange rate from the inner core to the surface.

Finally, a last crucial aspect concerns the description of the ocean crystallization and the treatment of the heat transfer throughout the entire H_2O mantles (inclucing solid and liquid layers). By combining numerical models describing the dynamics of the water ocean and the ice shells (low-pressure outer ice layer and high-pressure inner ice layer), we quantify the crystallization rate of the ocean and compare the modeled structure to the available gravity and topography data ([8]). The main objective of this work is to provide theoretical constraints on the possible evolutionary path followed by the internal ocean since its formation.

[1] Iess et al. *Science*, 337, 457 (2012). [2] Baland et al. *A&A*, 530, A141 (2011). [3] Baland et al. *Icarus,* in revision. [4] Béghin et al., *Icarus*, 218, 1028–1042 (2012). [5] Mitri et al. *Icarus*, in revision. [6] Nimmo and Bills, *Icarus,* 208, 896–904 (2010). [7] Hemingway et al., *Nature* 500, 550–552 (2013), [8] Lefevre et al., submitted to *Icarus*. [9] Niemann et al. *JGR*, 115, E12006 (2011). [10] Castillo-Rogez and Lunine, *GRL* (2010). [11] Tobie et al. *Titan book, Cambridge, in press* (2013). [12] Monteux et al. submitted to *Icarus*. [13] Bollengier et al., *Geochim. Cosmochim. Acta* 119, 322-339 (2013). [14] Bezacier et al., submitted to *PEPI*. [15] Tobie et al. (2012), *ApJ*, 752:125.

Acknowledgements: The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013 Grant Agreement no. 259285), from the Agence Nationale de Recherche (ANR Accretis, France), from the University of Nantes (France) and from the Region Pays de la Loire (France).

THE PRESERVATION OF ORGANICS AND BRINES IN LOW-TEMPERATURE AQUEOUS GLASSES.

J. D. Toner[1], D. C. Catling[1], and B. Light[2]
[1]University of Washington, Dept. Earth & Space Sciences, Seattle, WA 98195, USA, [2]Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, Washington, USA. (e-mail: toner2@uw.edu)

Introduction: We have investigated supercooling and vitrification in aqueous salt solutions during slow cooling (~0.2 K min^{-1}) experiments[1]. Remarkably, we find that slowly cooled $Ca(ClO_4)_2$ and $Mg(ClO_4)_2$ solutions do not crystallize during cooling, but harden into a glass (i.e. vitrify) near –120°C, even when mixed with soil. Vitrification occurs when the viscosity of a cooled solution increases to ~10^{13} poise, at which point the liquid structure becomes literally 'frozen' in place[2]. Low-temperature glasses are astrobiologically significant because vitrification is a widely used technique to preserve organisms in a prinstine state, such that they remain viable after rewarming[3]. Here, we explore the possibility that brines preserved as low-temperature glasses are useful for studying the aqueous chemistry and habitability of icy worlds.

Experimental Supercooling Measured in Aqueous Electrolyte Solutions: We studied supercooling/vitrification in concentrated $MgSO_4$, $MgCl_2$, $CaCl_2$, NaCl, $NaClO_4$, $Mg(ClO_4)_2$, and $Ca(ClO_4)_2$ solutions by slowly cooling solutions in a large polystyrene insulating block with a central cavity for holding the salt solutions. After adding a salt solution in a plastic bag to the cavity, we cooled the insulating block using liquid nitrogen and monitored the temperature of the salt solution over time with a Platinum Resistance Thermometer. Through inspection of the resulting temperature profile, we identify the precipitation and melting of solid phases by the heat of crystallization/dissolution.

Salt solutions that vitrify are easily distinguished from crystallizing solutions by the lack of temperature excursions from crystallization/melting (Fig. 1). Visually, vitrified solutions appear identical to liquid solutions and are distinct from opaque crystallized solutions (Fig. 2); however, vitrified solutions do not flow. In our slow cooling experiments, only $Ca(ClO_4)_2$ and $Mg(ClO_4)_2$ solutions vitrify; however, any brine will vitrify given a high cooling rate[2].

Low-Temperature Glasses on Icy Worlds: Several icy bodies in the solar system are thought to contain subsurface oceans[4,5]. Due to the low temperatures on the surfaces of the outer icy planets, subsurface brines exposed to the surface by convection of ice or cryovolcanism would freeze rapidly, leading to vitrification. If such exhumation processes occur, then glasses originating from subsurface oceans should be found on planetary surfaces and in ejecta from cryovolcanism. These glasses would preserve the aqueous chemistry of the source brines and any putative organics/life in a pristine state.

The preservation of orgamics. Organic molecules within vitrified brines would be preserved without deformation; in contrast, crystallization deforms cellular structures[6]. Glasses are also optically clear, which might facilitate the identification of organisms by future robotic missions (Fig. 2).

The preservation of brines. Aqueous glasses form from a parent liquid. As a result, the presence of glassy brines on the surface of an icy planet would indicate the aqueous history. Furthermore, glasses would preserve the aqueous chemistry in an uncrystallized state, so that the chemical composition of glasses directly reflects the parent brine composition.

References: [1] Toner et al. *Icarus*, in revision. [2] Angel & Sare (1970), *J. Chem. Phys.*, 52, 1058. [3] MacFarlane (1987), *Cryobiology*, 24, 181-195. [4] Schubertet al. (2010), *Space Sci. Rev.*, 153, 447-484. [5] Sohl et al. (2010), *Space Sci. Rev.*, 153, 485-510. [6] Han & Bischof (2004), *Cryobiology*, 48, 8-21.

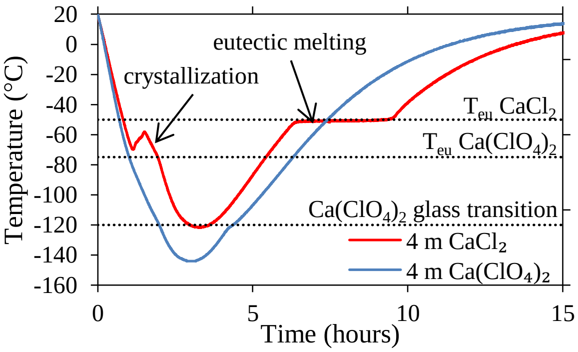


Fig. 1. Temperatures measured during cooling and warming of 4 m $CaCl_2$ and $Ca(ClO_4)_2$ solutions, indicating crystallization in the $CaCl_2$ solution, but none in the $Ca(ClO_4)_2$ solution.

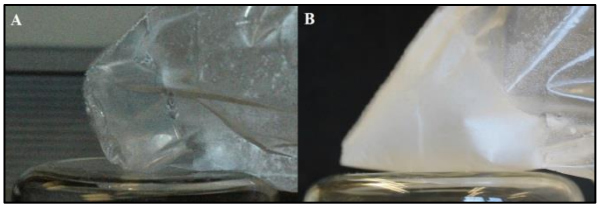


Fig. 2. (A) A clear, translucent, vitrified solution of 4 m $Ca(ClO_4)_2$. (B) a solution of 1.65 $MgSO_4$ cooled to a eutectic solid.

IMAGING SPECTROSCOPY AS A KEY TECHNIQUE TO CONSTRAIN HABITABILITY AND ORIGINS ON ICY WORLDS.

F. Tosi[1], G. Piccioni[1], M. C. De Sanctis[1], F. Capaccioni[1], G. Filacchione[1], P. Cerroni[1], M. T. Capria[1], [1]INAF-IAPS Via del Fosso del Cavaliere 100, I-00133 Rome, Italy, federico.tosi@iaps.inaf.it.

Introduction: In this paper we present some notable science cases where the imaging spectroscopy remote sensing technique will be crucial to constrain the potential habitability of several icy bodies that will be closely explored in the future.

Icy Galilean satellites: On Europa and Ganymede, the presence of large quantities of brine and sulphate salts in certain deposits may reflect the composition of subsurface liquid source reservoirs [1].

Onboard the JUpiter ICy moons Explorer (JUICE), hyperspectral imaging in the visible and near infrared range will be obtained by the Moons And Jupiter Imaging Spectrometer (MAJIS). Broadly regional hyperspectral mapping with spatial resolution between 2 and 3 km/px is expected to be achieved over more than 50% of the surface of Ganymede, while very detailed compositional mapping will be performed on several selected sites of interest. On Europa, the ability to perform two close flybys will eventually allow a thorough characterisation of some sites that are currently ranked at very high priority for both astrobiology and geology.

Enceladus: In situ measurements by Cassini showed that plume gas emanating from Enceladus consists primarily of water vapour and about ~5–10% other volatiles. The main volatile species are CO_2, NH_3 and a mixture of organic gases [2]. Amongst the latter are lightweight molecules like methane, acetylene and propane, but recent measurements also indicate even higher molecular weight compounds with masses exceeding 100 amu and aromatic organics [3]. Cassini's Visual and Infrared Mapping Spectrometer (VIMS) was able to measure the composition and the temporal evolution of the plume of Enceladus [4,5]. However, due to prominent absorption by water ice, the signal/noise ratio at wavelengths longer than 2.8 µm is too low to secure identification of all the volatile compounds and organic possibly present on the surface.

Titan: Only a few absorptions have been unambiguously detected in Titan's methane windows from remote sensing observations carried out in Cassini flybys. Evidence from VIMS infrared spectra suggests CO_2 frost [6], and liquid ethane in Ontario Lacus [7]. Although the exact blend of hydrocarbons in polar lakes and seas is unknown, liquid methane is almost certainly present. Finally, the correlation between the 5-µm-bright materials and RADAR-empty lakes suggests the presence of sedimentary or organic-rich evaporitic deposits in dry polar lakebeds [8].

A broader understanding of the surface composition of Titan will only be gathered by using a spectral mapper onboard a future dedicated orbiter mission. The augmentation of the sensitivity range beyond 5 µm would enable the identification of diagnostic signatures of several organic compounds likely to be present on Titan's surface [9,8].

Uranian moons: In the framework of future missions being proposed for the exploration of the Uranian system, the inclusion of an imaging spectrometer in the near infrared range (up to at least 5 µm) will make it possible to unveil the surface composition of the moons by identifying and mapping various chemical species with particular emphasis on non-water ice, visually dark materials. Joint spectroscopic and geologic measurements could provide important information on the role of processes that, at various spatial scales, led to the exchange of material between the surface and the subsurface as well as of those responsible for the exogenic activity.

Ceres: In April 2015, NASA's Dawn mission [10] will enter orbit around Ceres, whose mass and dimensions do not exclude the undifferentiated or partially differentiated body without icy mantle. The Visible and Infrared Mapping Spectrometer (VIR) onboard the spacecraft [11] will then perform a thorough mineralogical investigation of its surface. A detection and mapping of salts and other aqueous minerals with Dawn's remote sensing instruments will constrain aqueous processes on Ceres.

Origins: Chemistry of the regular satellites of the giant planets can be directly related to a physical process similar to the one that, at a larger scale, led to the formation of the planets themselves. The evolution of geochemical processes in the satellites can be constrained by a detailed mapping of the distribution of volatile and organic compounds.

References: [1] Dalton et al. (2010) *Geophys. Res. Abstracts*, 12, EGU2010-2270-1. [2] Waite et al. (2009) *Nature*, 460, 487-490. [3] Waite et al. (2011) *LXII LPS*, abstract n°1608. [4] Hedman et al. (2009) *ApJ*, 693, 1749-1762. [5] Hedman et al. (2013) *Nature*, 500 (7461), 182-184. [6] McCord et al. (2008) *Icarus*, 194, 212-242. [7] Brown et al. (2008) *Nature*, 454 (7204), 607-610. [8] Barnes et al. (2011) *Icarus*, 216, 136-140. [9] Stofan et al. (2007) *Nature*, 445, 61-64. [10] Russell and Raymond (2011) *Space Sci. Rev.*, 163, 3-23. [11] De Sanctis et al. (2011) *Space Sci. Rev.* 163, 329-369.

Returning Samples from Icy Enceladus Peter Tsou1, Ariel Anbar2, Donald E. Brownlee3, John Baross3, Daniel P. Glavin4, Christopher Glein5, Isik Kanik6, Christopher P. McKay7, Hajime Yano8, Peter Williams2 and Kathrin Atwegg9 [1]Sample Exploration Systems, [2]Arizona State University, [3]University of Washington, [4]NASA Goddard Space Flight Center, [5]Carnegie Institution of Washington, [6]Jet Propulsion Laboratory California Institute of Technology, [7]Ames Research Center, [8]Japan Aerospace of Exploration Agency, Institute of Space and Astronautical Science, [9] University of Bern.
Email: tsou.peter@gmail.com.

Introduction: From the first half century of space exploration, we have returned samples only from the Moon, comet Wild 2, the Solar Wind and the asteroid Itokawa. The in-depth analyses of these samples in terrestrial laboratories have yielded detailed chemical information that could not have been obtained without the returned samples. While obtaining samples from Solar System bodies is transformative science, it is rarely done due to cost and complexity. The discovery by Cassini of geysers on Enceladus and organic materials in the ejected plumes indicates that there is an exceptional opportunity and strong scientific rationale to do a low-cost flyby sample return mission. The earliest low-cost possible flight opportunity is the next Discovery Mission [Tsou et al 2012].

Enceladus Plume Discovery: While Voyager provided evidence for geologically young regions on Enceladus, Enceladus' plumes, active tectonics, and high heat flux were discovered by Cassini. Enceladus also appears to be the only known Solar System body outside of Earth where samples of recently frozen liquid water can be accessed from space, as the jets conveniently enable sample collection in a flyby without landing or surface contact, similar to Stardust and Hayabusa.

Cassini in situ Findings: Cassini has made many key discoveries at the Saturn system, including the fragmentation of relatively heavy organics from the plumes of Enceladus. Four prime criteria for habitability are liquid water, an energy source, organics and nitrogen [McKay et al. 2008, Waite et al. 2009, Postberg et al. 2011]. Out of all the NASA designated habitability targets, Enceladus is the single body that presents the clearest evidence for all four criteria. Significant advancement in assessing the biological potential of Enceladus can be made on returned samples in terrestrial laboratories where the full power of state-of-the-art laboratory instrumentation and procedures can be used. Without serious limits on power, mass or even cost, terrestrial laboratories provide the ultimate in analytical capability, adaptability, reproducibility and reliability.

What Questions can Samples Address? Samples collected from the Enceladus plume will enable a thorough and replicable search for possible extraterrestrial organisms and biosignatures [Glavin et al. 2011], which would propel our understanding of the habitability of the subsurface ocean of Enceladus. By searching for amino acids and peptides, nucleotides and nucleic acids, determining the sequences of any oligomers, assessing chirality and chemical disequilibrium, and measuring isotope ratios, we can formulate a new set of hypotheses to address many of the key science questions required for investigating the stage of extraterrestrial life at Enceladus beyond the initial four factors of habitability. At a broader level, Enceladus is offering us a unique opportunity to search for new insights into the puzzling transition between the ubiquitous prebiotic chemistry of asteroids and comets, and the biochemistry at the root of all known life. There is also much to be learned about the geochemistry of oceans inside icy worlds as a general phenomenon by studying Enceladus as a test case.

Criticality of Laboratory Analyses: - For extraterrestrial organic compound analyses such as chirality and compound-specific isotope ratio determination, the repeatable robustness of laboratory measurements is essential. In general, these analyses require a variety of chemical extraction and derivatization steps prior to analysis that are adapted to the sample and procedures that can be modified according to the results obtained. The Stardust mission is an excellent example of the challenges in the analysis of organics. Confirmation of the cometary origin of the amino acid glycine from comet Wild 2 was obtained 3 years after the samples were returned to Earth. This long period of laboratory testing and development allowed several modifications to the extraction protocol, involving multiple analytical techniques and instrumentation.

In Situ Measurement: Cassini results have suggested the existence of larger organic molecules with intriguing astrobiological possibilities in both the Enceladus jets. The proposed LIFE payload would include a mass spectrometer with significantly greater mass resolution than the 99 amu resolution of Cassini instruments. We would also carry a camera and a dust counter to capture ephemeral aspects of the plume not captured in the samples. In situ measurements provide essential context to the returned samples.

References: Tsou et al., Astrobiology 2012. McKay et al. Astrobiology 2008. Waite et al. Nature V 460 I 7254, 2009. Postberg et al. EPSC 642P 2011. Glavin et al., LPSC, #5002, 2011.

HEAT GENERATED BY OCEAN TIDES ON ICY SATELLITES IN THE SOLAR SYSTEM. R. Tyler, Dept. Astronomy, University of Maryland at College Park; Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Code 698; Greenbelt, MD 20771; robert.h.tyler@nasa.gov

Observations by the Galileo and Cassini spacecrafts have provided a strong indication that our massive water ocean is only one of at least several others in the Solar System. It seems clear that these oceans would have long ago frozen if not for an internal heat source. It also seems clear that in at least some of these cases (e.g. Enceladus), the heat sources previously presumed are insufficient. Recently, it has been shown by the author that if these oceans occupy one of several plausible resonant configurations, then the tidal response and associated dissipative heat can easily maintain liquid oceans on most of the large satellites in close orbits. It has also been shown that these resonant configurations are not just possible but may be inevitable because an ocean attempting to freeze will be pushed into the resonant configurations, with the increase in heat acting to stall further freezing.

More specifically, study of the parameter space of ocean tidal scenarios (where the parameters controlling the tidal response act as coordinates) show that energetic, resonantly forced tidal scenarios are stable configurations, at least until the available tidal energy in the orbit has been expended. A satellite with thick ice and no water ocean is possible only if one or more of the following apply: 1) There was never once a liquid ocean; 2) Available tidal forces were once insignificant, allowing the ocean to freeze; 3) The idealizations used in this study were once invalid for the ocean considered.

In this study, the most important idealizations susceptible to break down are the following: 1) Assumption that a global ocean is maintained; 2) Assumption that the primary effect of ice cover on the ocean is to lower the dissipation time scale. Work in progress shows, however, that the primary conclusions drawn from the idealized study may be maintained when these assumptions are relaxed: The primary effect of thick ice on the ocean tidal response indeed appears to be in decreasing the dissipation time scale (and only secondarily on altering the ocean's eigenmodes of oscillation); The global ocean is a requirement for ease in calculation, it is not required for the validity of the process identified whereby oceans can be stabilized in near resonant configurations; The process identified also extends to baroclinic modes and non-synchronously rotating bodies. A forward speculation is therefore that liquid oceans may be very common in the Universe because while tidal forces are available the oceans appear to be difficult to freeze.

THERMODYNAMIC CONSTRAINTS ON OCEAN STRUCTURE AND WATER-ROCK CHEMISTRY IN THE LARGE ICY SATELLITES.

S. Vance[1], J. M. Brown[2], C. Choukroun[1], and C. Sotin[1], Jet Propulsion Laboratory, Caltech, (svance@jpl.nasa.gov), [2]Department of Earth and Space Sciences, University of Washington, Seattle.

Introduction: Supporting life in icy world oceans may require global seafloor chemical reactions between water and rock. Such interactions have typically been regarded as limited in larger icy worlds such as Ganymede and Titan, in which ocean depths approach 800 km and GPa pressures (>10katm), predicted to create dense ice phases V and VI that cover the rocky seafloor. We evaluate factors that might lead to more extensive water rock chemistry by predicting water ice freezing and geothermal gradients in the interiors of the large icy satellites Ganymede, Callisto, and Titan. Accounting for available measurements of gravitational moments of inertia allows us to estimate depths to the rock interface. For Ganymede we compute the size of an iron-bearing core. New equations of state allow us to assess the influence of ocean salinity on the thickness of layers of ice I-II-III-V-VI in the interiors of these objects, and to infer associated ocean dynamics. Ocean compositions with salt or ammonia have less high-pressure ice, and can exist in the presence of ice III and II. In some model oceans, high-pressure ice phases become buoyant relative to surrounding fluids, implying frazil-like upward snows, interlayered liquids and ices, and fluids in direct contact with rock. We discuss the roles of dissolved constituents in the large icy satellites, consequences for habitability, and prospects of future missions for testing these predictions.

Aqueous Ammonia in Titan's Ocean: In this abstract, we present recent results applied to Titan's internal ocean [1]. Ammonia is stable in the outer solar system owing to the temperatures encountered there during solar system formation. To accurately describe the consequences of including ammonia in oceans on Titan or elsewhere, we evaluated thermodynamics of the ammonia water system to 1.8 GPa pressure. Using sound velocity measurements obtained in our laboratory, we constructed a self-consistent thermodynamic framework for the binary ammonia-water system. The methodology is similar to that used previously [2]. We also include sound velocity data for pure ammonia from [3]. Densities, thermal expansion, and heat capacity differ substantially from those of [4] but are consistent with [5]. Ice properties and phase boundaries were obtained following [6]. Application to Titan's interior structure uses the approach recently applied to Ganymede for oceans dominated by $MgSO_4$ [7]. We demonstrate absence of high pressure ices in a 15 Wt% ammonia ocean [e.g. 8], consistent with constraints on internal structure [9], for highest heat flux considered.

References: [1] Béghin et al. (2012) *Icarus 218* 1028–1042. [2] Vance S. and Brown J. M. (2013) *Geochim Cosmochim Acta, 90,* 1151–1154. [3] Abramson et al. (2009) *J. Chem. Eng. Data* 53, 1896-1897. [4] Croft et al. (1988) *Icarus, 73,* 279-293. [5] Tillner-Roth R. and Friend D. G. (1998) *J. Phys. Chem. Ref. Data* 27, 45–62. [6] Choukroun M. and Grasset O. (2010) *J. Chem. Phys. 133,* 144, 502. [7] Vance S. et al. (under revision). [8] Fortes A. G. (2000) *Icarus 146*, 444-452. [9] Iess L. et al. (2010) *Science 327*, 1367-1369.

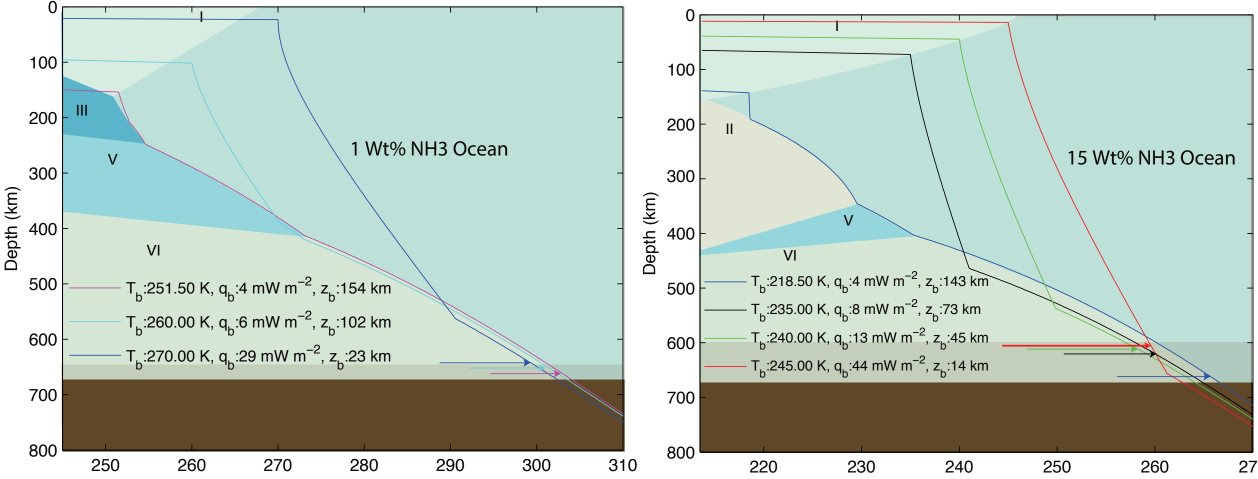


Figure 1. Geothermal profiles for a differentiated Titan obtained using new thermodynamic data. T_b is the temperature at the bottom of the ice I layer, z_b is corresponding thickness, and q_b is heat flux for idealized conductive cooling with k~1/T [6]. Arrows indicate rock interface depths consistent with bulk density constraints [8]. The 15 Wt% ocean (right; red) has liquid in contact with rock. Ammonia-bearing liquids are always less dense than high pressure ice phases.

Enceladus Plume Composition: Clues to Habitability. J. H. Waite, Jr.[1], T. Brockwell[1], W. S. Lewis[1], B. Magee[1], W. B. McKinnon[2], Olivier Mousis[3], and A. Bouquet[3] ([1]Southwest Research Institute, San Antonio, TX 78228, [2]Washington University in St. Louis, MO 63130, [3]Institut UTINAM, UMR CNRS 6213) .

The Cassini-Huygens Ion Neutral Mass Spectrometer (Cassini INMS) has obtained valuable data on the composition and structure of the Enceladus plume during several flybys of the Cassini spacecraft: E2 [1], E3, E5 [2], E7, E14, E17, and E18. Flybys E3 and E5 had flyby velocities of 16.6 and 17.7 km per second, respectively, due to the large inclination of the Cassini orbit plane with respect to Saturn's equatorial plane. In the case of the E7, E14, E17, and E18 flybys, Cassini passed directly through the center of the plume at low (70-100 km) altitude on a prograde trajectory in Saturn's equatorial plane with velocities of 7 to 8 km per second.

The plume composition observed by INMS at the various flyby velocities is strongly dependent on the flyby velocity. In particular, decreases in the water to molecular hydrogen density and the carbon dioxide (mass 44) to carbon monoxide (mass 28) ratios were observed as the flyby speed increased. We have investigated these changes using collisional models that can determine the effect of the impact of gas molecules and micron-sized ice grains on the titanium surface of the INMS closed ion source. At flyby velocities above 16 km per second the subsequent release of titanium vapor induces chemical changes in the incoming gas. At all velocities some molecular fragmentation is possible. However, very little effect is expected or observed for the low velocity flybys, and we find very similar and reproducible spectra for the low velocity E14, E17, and E18 flybys, which we interpret as the "true plume composition."

During the high velocity flybys we find that water can be converted to molecular hydrogen through chemi-absorption of the water onto the fresh titanium surface created from an ice grain impact. Increases in carbon monoxide cannot, however, be explained by this process, nor can the increases observed in C3 and C4 unsaturated hydrocarbons. These high velocity effects are likely due to molecular fragmentation of organic macromolecules. Organic macromolecules (dust grains) can be dissociated by impact on the titanium surface and observed as low mass molecular fragments in the mass spectra from the plume during high velocity flybys. This provides an additional organic component to the plume outgassing of unknown composition, but likely containing PAHs and oxygenated organic polymers (e.g., carboxylic acids and alcohols).

Interpretation of the INMS plume composition data is challenging but provides important clues to the nature of the plume source(s) and to the origin and evolution of Enceladus as well as to the conditions for habitability in the moon's interior. Robust species identifications include CO_2, CH_4, NH_3, and (obviously) H_2O. The CO_2/CH_4 ratio for the low-velocity flybys is >1, and given that CH_4 is more volatile than CO_2, implies predominance of CO_2 at the plume source (or sources) or trapping of CH_4 in clathrates. In terms of possible ocean chemistry, sufficiently oxidized conditions for CO_2 stability are indicated, but thermochemical equilibration with CH_4 cannot be assumed without independent constraints on the temperatures of extant or past hydrothermal systems. On the other hand, the presence of NH_3 and organic macromolecules implies that such hydrothermal systems could not have been so hot or oxidizing as to destroy NH_3 and complex organics. The stability of organic molecules is an important prerequisite for prebiotic evolution.

References: [1] Waite et al. (2006) *Science, 311,* 1419-1422. [2] Waite et al. (2009), Nature, *460*, 487-490.

ENERGY IMPLICATIONS OF FRAGMENTATION PROCESSES IN EUROPA'S ICE SHELL.

C. C. Walker[1] and B. E. Schmidt[2], [1]Georgia Institute of Technology, Atlanta, GA 30312 (cat.walker@eas.gatech.edu), [2]Georgia Institute of Technology, Atlanta, GA 30312 (britneys@eas.gatech.edu).

Introduction: Because of the important role that the ice shell plays in Europa's evolution as a mediator between its interior and surface, a study of Europa's habitability must consider dynamics within its near-surface ice shell. Europa's surface is riddled with fractures, which betray a long history of geophysical activity. With an ~100 km deep ocean lying atop a silicate interior (e.g. [1], [2], [3]), Europa is an intriguing target for astrobiological study. On the Earth, ice and the ice-water interace are repositories of life (e.g., [4], [5]). Thus, ice cycling may provide nutrients to the Europan ocean, and pores, basal cracks, and grain boundaries in its ice may serve as harbors for life. Such ice shell-ocean communication must occur geologically short timescales in order for Europa to be habitable. One way in which this can occur is through disruption of the ice shell. Thus active geological areas have strong implications for the recycling of the ice shell, and the habitability of the ice shell itself.

Application of Fragmentation Theory: Recent work suggests that chaos terrain formation may include a collapse phase, and that the eventual appearance of the chaos terrain is determined in part by the fracture density within the background terrain [6]. In studying the size distribution of fragments in Europa's chaos regions, it is possible to back out physical properties of the ice, such as material strength and cohesion properties and most importantly, the energy necessary to create a fragmentation event using fragmentation theory. Fragmentation theory describes the breakage of a body into several pieces (e.g. [7]). Dynamic fragmentation modeling in elastic and plastic solids is primarily a statistical study of material behavior, and is categorized into three stages: (1) crack nucleation; (2) crack propagation; (3) fragment coalescence.

Implications for Energy within the Ice Shell: Different patterns of fragmentation can produce different estimates of material properties and the energy required to produce the fragmentation event, examples of which are shown in Fig. 1 and defined in [8]. A characteristic length scale is based on the local balance of kinetic and fracture energy and layout of fragments. In this theory, we consider a body to break apart into a certain collection of fragments. Each fragment takes kinetic energy as the object breaks up, and this energy goes into local expansion and rigid-body motion. Local kinetic energy then contributes to further failure. A characteristic length scale for fragmentation is based on the local energy balance of potential, kinetic, and fracture energies in a given material [8]. Through the balance of energies, [9] determined the energy driving fragmentation in two dimensions based on material density, strain rate, surface energy, propagation speed, and fracture toughness.

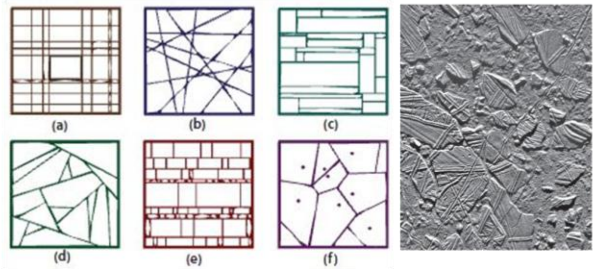


Figure 1. *Right: Common geometric fragmentation patterns, picture from [9]; Left: PIA01403 - chaos region on Europa taken by Galileo in 1998; (a) Random lines of equal length; (b) Pickup Sticks/Mott fragmentation; (c) Sequential Segmentation; (d) Same as (c) with conditions on shortest dimension; (e) Randomly distributed/oriented segments; (f) Voronoi-Dirichlet fragmentation. Each type is associated with specific length scales and fragmentation types.*

Here, we will present an estimate of the energy released in chaos terrain collapse through application of fragmentation theory and iceberg capsize analysis. This approach allows us to understand the mechanism behind dynamic collapse of the ice shell as well as its potential for mixing material in the upper ~5km of the ice shell downward, providing input to a recycling ice shell. Thus, in determining the fragment size distribution, and thus the dynamic history of that ice, we will constrain physical properties of the ice shell and their implications for Europa's habitability.

References: [1] Khurana, K. K., et al. (1999) *Nature, 395*, 777-780. [2] Kivelson, M. G., et al. (1999) *JGR*, *104*, 4609-4625. [3] Zimmer, C., Khurana, K. K. and Kivelson, M. G. (2000) *Icarus, 147*, 329-347. [4] Priscu, J. C. and Christner, B. C. (2004) *Microb. Div. and Bioprospecting*, 130-145. [5] Deming, J. W. and Eicken, H. (2007) *Planets and Life*, 292-312. [6] Schmidt, B. E. et al. (2011), *Nature, 479*, 502-505. [7] Grady, D. E. and Kipp, M. E. (1995) *Int. J. Sol. and Struct., 32*, 2779-2791. [8] Grady, D. E. (1982) *J. Applied Phys., 53*, 322-325. [9] Grady, D. E. (2009) *Int. J. Fracture, 163*, 85-99.

The Influence of Magnetospheric Plasma on Magnetic Sounding of Europa's Interior Oceans.

J. H. Westlake[1], A. M. Rymer[1], J. C. Kasper[2,3], R. L. McNutt[1], H. T. Smith[1], M. L. Stevens[3], C. Parker[1], A. W. Case[3], G. C. Ho[1], D. G. Mitchell[1], [1]Johns Hopkins University Applied Physics Laboratory, [2]University of Michigan, [3]Harvard Smithsonian Center for Astophysics.

The strongest evidence for the existence of a liquid ocean at Europa has been provided via magnetic field measurements that support the existence of a subsurface conducting layer. This evidence was derived by comparing in situ magnetic field measurements with different induced magnetic field models, including different scenarios for the bulk composition and differentiation of Europa's subsurface region Khurana et al [1998] concluded that the most likely scenario was a fully conducting layer beneath Europa's water-ice surface. While the magnetic field signature could be due to a solid metal-rich layer, other data on the differentiation and average mass density of Europa effectively rule out this possibility [Anderson et al., 1998]. The most likely scenario is that the conducting layer is a liquid ocean between 100 and 170 km thick with the conductivity generated by dissolved salts such as sodium chloride and, especially, ammonia - that not only provide free ions to carry current but also acts as an anti-freeze allowing water to be in liquid form at low temperatures.

If Jupiter's magnetosphere were otherwise empty, de-convolving the induced field from Europa's interaction with the Jovian background field would be a nontrivial task. However Jupiter's magnetosphere is full of ionized plasma mostly from its volcanic moon Io, but also from Europa, the other Jovian satellites, and from Jupiter itself. In magnetohydrostatic equilibrium the magnetic field is coupled to the ambient plasma by the relation

$$\nabla p = j \times B + \rho g$$

where the gradient of the particle pressure (p) is balanced by the magnetic tension and gravity. This relation also gives the familiar concept of the plasma β. The in situ magnetic field measurements from any proposed Europa mission will be influenced by the multitude of plasma regions encountered resulting in the following sensitivities: 1) changes in the magnetic field to maintain pressure balance in the plasma; 2) the response of the magnetic field to currents in the plasma and 3) Europa's plasma exosphere and atmosphere. Estimates of the plasma pressure contribution to the magnetic field measurements range from ~20 nT in the magnetospheric lobes to over 200 nT within the plasma sheet. This contribution is substantial compared to Europa's induction response to Jupiter's cyclical field component due to its internal conductivity, which is about 250 nT near the surface [Kivelson et al., 2000; Khurana et al., 2009]. From this relation and the estimates of its contribution to the measurements it is clear that the particle pressure is the crucial measurement for correcting the magnetic field measurements.

The Europa Clipper mission will make repeated flybys of Europa at different altitudes and locations in order to characterize Europa's induced magnetic field. Observations of the variability of this field with Jupiter's 10 hour rotation period and Europa's 85 hour orbital period will be used to determine what ocean properties are consistent with the observations. The mission concept relies on observations of Europa's induction response over a variety of Jovian system III longitudes and true anomalies, and will therefore require plasma corrected magnetic sounding measurements for every flyby. In this paper we detail the crucial measurements of the Jovian and Europan plasma environments that are necessary to magnetically sound Europa. We specifically discuss the contribution of Jovian magnetospheric plasma and Europan ionospheric plasma to the precision of the subsurface magnetic sounding measurement. We introduce a candidate suite of instruments, consisting of two Faraday cups and a retarding potential analyzer, that can provide the high quality plasma measurements that are crucial to the success of a Europa magnetic sounding experiment.

References:

Khurana, K. K., et al. "Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto." Nature 395.6704 (1998): 777-780.

Khurana, Krishan K., et al. "Electromagnetic induction from Europa's ocean and the deep interior." Europa, Edited by Robert T. Pappalardo, William B. McKinnon, Krishan K. Khurana; with the assistance of René Dotson with 85 collaborating authors. University of Arizona Press, Tucson, 2009. The University of Arizona space science series ISBN: 9780816528448, p. 571 1 (2009): 571.

Kivelson, Margaret G., et al. "Galileo magnetometer measurements: A stronger case for a subsurface ocean at Europa." Science 289.5483 (2000): 1340-1343.

Anderson, J. D., et al. "Europa's differentiated internal structure: Inferences from four Galileo encounters." Science 281.5385 (1998): 2019-2022.

ON DETECTABILITY OF AMINO ACIDS IN THE PLUMES OF ENCELADUS USING FAR-INFRARED SIGNATURES.

D.P. Winebrenner[1,2] and M.H. Arbab[1], [1]Applied Physics Laboratory, Box 355640, University of Washington, Seattle, WA 98195 (dpw@apl.washington.edu), [2]Department of Earth and Space Sciences, Box 351310, University of Washington.

Introduction: Ion and Neutral Mass Spectrometer (INMS) data from the Cassini spacecraft indicate a variety of small organic molecules in the outflow from plumes at the south pole of Enceladus [1], which may result from fractionation within the instrument of larger organics [2]. The discovery that ejected solids are dominated by salt-rich particles strongly suggests the existence of subsurface water in prolonged contact with rock [3], and so motivates alternative methods for detecting organics in icy particles in the plumes. Among the organics of particular interest would be amino acids [2].

Spectroscopic methods to detect amino acids could be advantageous in that instrumental fragmentation would be avoided, but sensivity to the low volumetric mass fractions indicated by INMS data [1] may present serious challenges. The Cassini Composite Infrared Spectrometer (CIRS) provides emission observations over an exceptional range of wavelengths (wavenumber) from 7 to 1000 microns (1428 cm^{-1} to 10 cm^{-1}), i.e., through the mid-IR and well down into the far-IR. The aim of our investigation is to understand whether data augmenting near-IR spectroscopy with mid- and far-IR observations, where amino acids are known to have additional resonances, offers opportunity for more sensitive or more specific detection of amino acids or other organics in icy particles.

Far-IR resonances of amino acids: Crystalline amino acids including L-glutamic, L-cysteine, L-histidine, L-arginine, and L-leucine display resonances useful for detection and discrimination against a background of sugars and other organics at 30 to 100 cm^{-1}, though detection may require volumentric abundances on the order of a few percent [4]. In a water ice matrix, however, impurities would be spatially concentrated by freezing in inclusions with sizes on the order a wavelength in size (at 100 cm^{-1}), with likely consequenses of signatures.

Laboratory Investigation: We have therefore begun using Terahertz Time-Domain Spectrometry in the laboratory to characterize spectral extinction of amino acids, both in crystalline form and in ice frozen from aqueous solutions. By utilizing an air-plasma source, we extend our measurements from roughly 10 cm^{-1} to 300 cm^{-1}, i.e., up to the boundary between the mid- and far-IR portions of the spectrum. New spectral structure between 100 and 300 cm^{-1} may offer means of more sensitive detection. We will present new data on amino acid absorption in this spectral range, both for crystalline forms and for frozen aqueous solutions, thus providing the first indication of optical path lengths that would be required for detection in this spectral region.

References: [1] J.H. Waite, Jr. et al. (2009) *Nature, 460*, 487-490. [2] C.P. McKay et al. (2012) *Planetary and Space Science, 71*, 73-79. [3] F. Postberg et al. (2011) *Nature, 474*, 620-622. [4] Y. Ueno et al. (2011) *Analytical Sciences 27*, 351-356.

THERMOPHYSICAL MODELING OF THE MEGAREGOLITH ON AIRLESS BODIES IN THE OUTER SOLAR SYSTEM: IMPLICATIONS FOR OCEANS AND HEAT FLOW ESTIMATES.

Stephen E. Wood[1], Stephen G. Griffiths[2], [1]Dept. of Earth and Space Sciences, Univ. of Washington, Seattle WA, 98195-1310, sewood@ess.washington.edu, [2]Univ. of Leeds, UK.

A key determinant for the existence, and the depth, of liquid oceans on icy worlds is the thermal conductivity, $k_{th}(z)$, of the "megaregolith" (porous outer layer of accumulated ejecta and impact-fractured material [1, 2]. Most studies of the interior thermal structure and evolution of icy worlds do not address the potential insulating effects of this layer, or assume it is negligible. But a quantitative justification is seldom given.

We know from remote measurements of thermal inertia on icy satellites that the surface value of k_{th} is very low, typically 0.001 $Wm^{-1}K^{-1}$ [e.g. 3,4]. And from studies of lunar regolith we know k_{th} can be 10 times greater just a few cm deeper due to a decrease in porosity from 60-70% at the surface to typical values (30-40%) for random close-packed particles [5]. But 0.01 $Wm^{-1}K^{-1}$ is still less than 1% of the conductivity of solid ice, and any further increase due to compaction may require lithostatic pressure >1 MPa [6,7].

The main obstacle to better estimates of megaregolith thermal effects is the paucity of information about its structure and composition (just as it is for most other aspects of icy world interiors!). But one mitigating feature of cold airless regolith is that k_{th} is largely independent of particle size at any depth where mechanical forces dominate van der Waals forces, *i.e.* for z>10m on Callisto [W14a]. The size dependence of k_{th} for regolith on the Moon and Mars is due to the radiative and/or gas components of conduction, but these are negligible in the upper 10 km of most icy bodies. The thickness of megaregolith on icy worlds is another important unknown, with estimates ranging from 100m to 10km [2,8,9]. But we note that even a 100m-thick layer can create a significant ΔT (**Fig. 1**).

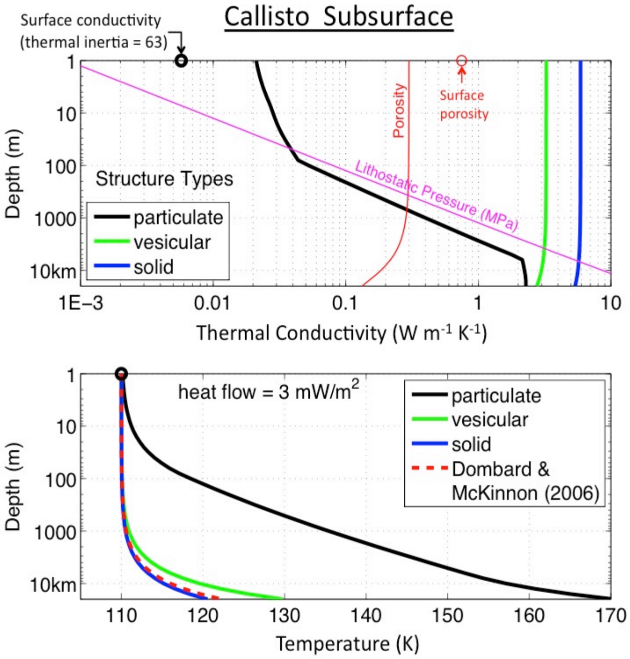


Figure 1 – Example model calculations for Callisto.

(Top) Model-calculated profiles of thermal conductivity, $k_{th}(z)$, in the upper 10 km using the MaxRTC Model [Wood, 2013, W13] for cases representing the wide range of possible physical structures: a nonporous solid (*blue line),* a vesicular solid – *i.e.* isolated pores – (*green line*), and uncemented particles – *i.e.* nearly isolated particles (*black line)*. Both the particulate and vesicular cases use the same porosity profile, $\Phi(z)$ (*red line*), illustrating that the continuity of the solid material is much more important than its porosity [10]. All cases assume a composition dominated by water ice, and include a T-dependent solid conductivity.

Calculated surface conductivity is 0.006 W/m/K for a 20 μm particles and Φ=60% (surface values are indicated by circles on the top axis), yielding a thermal inertia of 63 J m^{-2} $s^{-1/2}$ K^{-1} – in line with observed values [3]. Particle size increases linearly with depth, but results are not sensitive to this assumption (see text). We assume Φ=30% at z=1m and calculate the decrease with depth based on data for hydrostatic compaction of granular ice [6].

(Bottom) Temperature profiles corresponding to the conductivity profiles above for a heat flow of 3 mW/m^2 [11] and an average surface temperature of 110 K. For comparison, a profile used to model crater topography relaxation [12] is also shown (*dashed red line*).

References: [1] Hartmann, W. K. (1973). *Icarus* 18:634–636. [2] Warren, P.H. (2011), *Met. & Planet. Sci.* 46, Nr 1, 53–78. [3] Spencer, J.R. (1987), *Icarus* 69:297-313. [4] Howett, C.J.A., J.R. Spencer, J.Pearl, and M. Segura (2010), *Icarus*, 206, 573-593. [5] Heiken et al. 1991, *Lunar sourcebook,* Cambridge Univ. Press. [6] Durham, W. B., McKinnon, W. B., & Stern, L. A. (2005), *GRL 32*(18). [7] Yasui, M., & Arakawa, M. (2009), *JGR:Planets*, *114* (E9). [8] Veverka, J., Thomas, P., Johnson, T. V., Matson, D., & Housen, K. (1986), In *Satellites* (Vol. 1, pp. 342-402). [9] Eluszkiewicz, J. (2004), *Icarus*, *170*(1), 234-236. [10] Hashin, Z. & S. Shtrikman (1962) *J. Appl. Phys.*, *33*, 3125-3131. [11] Castillo-Rogez, J. C., and T.B. McCord (2010), *Icarus* 205, 443–459. [12] Dombard, A. J., and W. B. McKinnon (2006), *JGR* 111, E01001. [W13] Wood, S. E. (2013), *LPI Contrib.*, *1719*, 3077, http://www.lpi.usra.edu/meetings/lpsc2013/eposter/3077.pdf [W14] Wood, S.E. (2014), in prep.

INVESTIGATING THE FORMATION, EVOLUTION, AND HABITABILITY OF THE GALILEAN SATELLITES WITH HIGH PERFORMANCE MASS SPECTROMETRY.

D. Wyrick[1], J. H. Waite, Jr.[1], T. Brockwell[1], M. McGrath[2], W.B. McKinnon[3], O. Mousis[4] and B. Magee[1] ([1] Southwest Research Institute, San Antonio, TX and Boulder, CO.; [2] NASA Marshall Space Flight Center, Huntsville, AL; [3] Washington University, Saint Louis, MO; and [4] CNRS Observatoire de Besancon, Besancon, France)

Introduction: High performance mass spectrometry (MS) allows for direct sampling of atomic and molecular species released through intense sputtering on the surface or outgassed volatiles from geologically active regions. New technologies, combining a cryotrapping inlet and multibounce time-of-flight ion optics, boost mass resolution ($M/\Delta M > 20{,}000$) and detection sensitivity (parts per 10^{12}, ppt) to unprecedented levels. In this talk, we detail the science objectives, develop the rationale for the measurement requirements, and describe potential instrument/mission methodologies for studying the formation, evolution, and habitability of the Galilean satellites, with emphasis on key measurements relevant to the proposed Europa Clipper mission.

Measurements of Key Species for Habitability: Both high mass resolution and high sensitivity are required to distinguish isotopologues of SO_2, CO_2, and other species as well as to identify complex organic molecules, measurements that are critical to answering questions of hydrothermal alteration, abiotic/biotic processes, and habitability on Europa, past and present.

Organics and the H, C isotopes of CO_2, CO, CH_4, C_2H_6, and higher order hydrocarbons: The mass resolution of our instrument can determine whether organics are present and what kind (i.e., hydrocarbons, nitriles, amines, alcohols, carboxylic acids). Measurements of the H and C isotopic ratios of carbon bearing compounds can help differentiate (e.g.) Fischer-Tropsch reaction (abiotic; [1]) from cometary (primordial; [2]) from biological [3,4] signatures, of key importance in understanding the potential and/or existence of habitability [5].

Measurement of ratios of key simple volatiles (NH_3 and N_2, CO, CO_2, and CH_4, HCN, O_2, H_2O and H_2): Volatiles ratios that source from Europa's oceans may represent an equilibrium, hydrothermally processed assemblage or a disequilibrium, comet-like assemblage. If the ratios appear consistent with thermochemical processing [6,7], then constraints on the temperature and oxidation state should be possible. Ongoing hydroxylation of mafic and ultramafic silicate minerals can act as a source of hydrogen [8,9], which can fuel microbial ecosystems [10].

H, O isotopes of H_2O: Cycles of vaporization and condensation of water ice lead to fractionation of the O isotopes in water. MS can distinguish between sources of water by measuring H isotopes in water [11,12,13], thereby constraining the past hydrothermal processing of interior minerals.

NH_3 and N_2 isotopes: Primordial N_2 and NH_3 have fundamentally different isotopic ratios, which can be measured to determine if the N_2 derives from primordial materials or has been altered as suggested by measurements at Titan [14]. From a habitability point of view, nitrogen is a biologically essential element, but once tied up as N_2, it is much less available for metabolic processes (life).

Argon: ^{40}Ar forms from the decay of ^{40}K in the crust and dissolved in ocean waters, and should remain trapped in the interior until geologic activity provides an opportunity of release into the exosphere. Detection of ^{40}Ar (which requires a very high sensitivity measurement) would indicate recent or ongoing surface-atmospheric interaction and potentially locate outgassing sites.

SO_2 isotopes: Sulfate salts have been taken as signatures of ocean chemistry (present day oxidation state and thus chemical potential for life) on Europa [15]. Measuring the SO_2 isotopes on the surface of Europa and in orbit closer to Io will allow comparisons to determine the sulfur's origin.

Conclusions: Improved MS performance will allow the measurement of isotopic composition and present day volatile ratios as well as the correct identification of complex organics, all essential to addressing the goal of understanding Europa's habitability.

References: [1] McCollom T.M. et al. (2010) *GCA*, *74*, 2717-2740. [2] Crovisier J. and Bockelee-Morvan D. (1999) *Space Sci Rev.*, *90*, 19-32. [3] Horita J. (2005) *Chem. Geol.*, *218*, 171-186. [4] Whiticar M.J. (1999) *Chem. Geol.*, *161*, 291-314. [5] Bradley A.S. and Summons R.E. (2010) *EPSL*, *297*, 34-41. [6] Shock E.L. (1990) *OLEB*, *20*, 331-367. [7] Shock E.L. and McKinnon W.B. (1993) *Icarus*, *106*, 464-477. [8] McCollom T.M. and Bach W. (2009) *GCA*, *73*, 856-875. [9] Mayhew L.E. et al. (2013) *Nature Geosci.*, 6, 478-484. [10] Kelley D.S. et al. (2005) *Science*, *307*, 1428–1434. [11] Kavelaars J.J. et al. (2011) *Astrophys. J. Lett.*, *734:L30*, 1-5. [12] Mousis O. (2004) *A&A*, *414*, 1165-1168. [13] Waite J.H. et al. (2009) *Nature*, *460*, 487-490. [14] Hutsemekers D. et al. (2009) *Icarus*, *204*, 346-348. [15] Brown M.E. and Hand K.P. (2013) *Astron. J.*, *145:110*, 1-7.

ICY SATELLITE SURFACE COMPOSITIONS FROM THERMAL INFRARED SPECTROSCOPY.

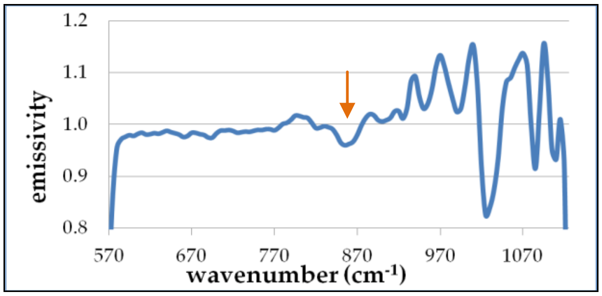
C. L. Young[1], J. J. Wray[1], R. N. Clark[2], K. P. Hand[3], J. R. Spencer[4], [1]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, [2]U.S Geological Survey, [3]Jet Propulsion Laboratory, [4]Southwest Research Institute.

Introduction: Spectroscopy of icy satellite surfaces can aid us in searching for the requirements of life on these worlds. Compositional studies of Saturn's icy satellites were one of the original primary science goals for Cassini's Composite Infrared Spectrometer (CIRS) [1]. However, to date, CIRS surface compositional studies have received less attention than measurements of atmospheres, surface temperatures and thermophysical properties across the Saturn system.

Cassini Visual and Infrared Mapping Spectrometer (VIMS) data from icy moons have shown tantalizing evidence for H_2O, CO_2, possible NH_3 and hydrous minerals, organics, metallic and oxidized Fe [e.g., 2-4], but the stronger fundamental spectral features in the mid-IR would allow confirmation of these constituents and more specific identifications. The spectral region covered by CIRS focal planes 3 and 4 is rich in emissivity features due to both simple and complex molecules [e.g., 5], but the study of emissivity variations in this region is often challenged by low signal-to-noise ratios for individual spectra. Our goal is to use Cassini CIRS to characterize the surface composition of icy moons. We present an approach to average CIRS spectra from the full icy moon dataset on the Planetary Data System (PDS) to increase signal-to-noise and use emissivity spectra to constrain surface compositions.

Methodology: Iapetus was selected as an initial case to test our approach, as its dark terrain appears spectrally complex to VIMS and has relatively high surface temperatures, which were expected to increase the IR signal. CIRS focal plane 3 (FP3) spectra from the PDS were obtained using the Vanilla software package. The Outer Planets Unified Search (OPUS) was used to select observations during which the dark material on Iapetus was illuminated by afternoon sunlight in order to assure the highest surface temperatures possible. Spectra from a single observation were selected in order to demonstrate the value of spectral averaging. The wavenumber form of the Planck blackbody equation was used to determine surface temperatures. Emissivities were calculated by dividing the CIRS average radiances by the blackbody radiance at each wavenumber.

Results and Discussion: The averaged emissivity spectra reveal a feature of interest at ~855 cm^{-1} (denoted by the orange arrow in the figure). This feature does not correspond to any known instrument artifact (D. Jennings, personal communication) and is the first FP3 spectral feature reported for an icy moon.



Elemental sulfur has a comparable spectral feature [6], but has another feature at ~660 cm^{-1} that is not observed in our CIRS spectrum. Some carbonates [7] and organics [5] absorb near 850 cm^{-1}, but both should also be detectable by VIMS and yet have not been reported to date. By contrast, across vast dust-covered regions of Mars, the only feature detectable at CIRS FP3 wavelengths is at ~840 cm^{-1} and is due to fine-grained silicate minerals, such as feldspars [8]. If silicates are present on Iapetus, then the extremely low thermal inertia values measured there [e.g., 9] are consistent with sub-micron-size grains [10].

Conclusions: We report the first tentative identification of a spectral feature from CIRS FP3 icy moon data, at ~855 cm^{-1}. Future studies will examine more data from Iapetus and other moons in search of emissivity features and will use laboratory analogs to identify ambiguous features. If no other features are found, we will use lab studies to assess what compositions would appear featureless in the mid-IR. Whether or not features are found will have implications for the suitability of mid-IR spectrometers to study icy moon surface compositions on future missions.

References: [1] Flasar F.M. et al. (2004) *Space Sci. Rev.*, *115*, 169–297. [2] Brown R.H. et al. (2006) *Science*, *311*, 1425–1428. [3] Cruikshank D.P. et al. (2008) *Icarus*, *193*, 334–343. [4] Clark R.N. et al. (2012) *Icarus*, *218*, 831–860. [5] Hand K.P. et al. (2009) in *Europa*, Eds. R. Pappalardo, W. McKinnon, & K. Khurana. Univ. of AZ Press. [6] Clark R.N. et al. (2007) USGS http://speclab.cr.usgs.gov/spectral.lib06. [7] Clark R.N. (1999) in *Manual of Remote Sensing, Volume 3, Remote Sensing for the Earth Sciences*, Ed. A. N. Rencz, John Wiley and Sons. [8] Christensen P.R. et al. (2004) *Science*, *305*, 837–842. [9] Howett C.J.A. et al. (2010) *Icarus*, *206*, 573–593. [10] Presley M.A. and Christensen P.R. (1997) *J. Geophys. Res.*, *102*, 6551–6566.

SAMPLE TUBE SEALING AND SAMPLE INTEGRITY ANALYSIS FOR FUTURE SAMPLE RETURN MISSIONS.

Paulo Younse[1], Katherine Accord[1], David Aveline[1], Xiaoqi Bao[1], Luther Beegle[1], Dan Berisford[1], Pradeep Bhandari[1], Charles Budney[1], Erol Chandler[1], Fei Chen[1], Nicole Chen[1], Moogega Cooper[1], Shirley Chung[1], Patrick DeGrosse[1], Emma Dodd[1], Matthew Fuller[1], Don Lewis[1], Kim Lykens[1], Mimi Parker[1], Rebecca Smith[1], [1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, paulo.j.younse@jpl.nasa.gov.

Introduction: Future exploration of icy worlds in-situ would provide a wealth of information without altering the sample of interest; however, there is a wealth of information which can be gathered from a potential sample return mission from icy worlds. Current efforts surrounding the future Mars sample return campaign will be useful to answer sample compatibility questions for samples which may react with the vessel used to contain it. Studies are being persued which provide a sealing methodology for a range of temerpatures, including those applicable to the icy-world envorinment.

The standards used to develop a sealing methodology for sample caching and return derives from the Mars 2020 Science Definition Team baseline for a caching system [1]. This takes into consideration the baseline maximum organic contamination (currently 10 ppb), inorganic contamination, leak rate, magnetic field exposure, and maximum temperature exposure.

Seal Designs: Six sealing designs were selected following a survey of the state-of-the-art sealing techniques [2]. Several seals were eliminated based on factors such as seal hermeticity, sample integrity, and dust tolerance resulting in a set of 3 Phase-II seal designs. Three seal prototypes are based on the Shape Memory Alloy (SMA) technology and the fourth seal mechanism is torque-actuated (Figure 1). Each SMA cap and plug uses expanding fins/ring to create a seal with the tube. It was important to have a non-heat based option, which the expanding torque plug fulfilled.

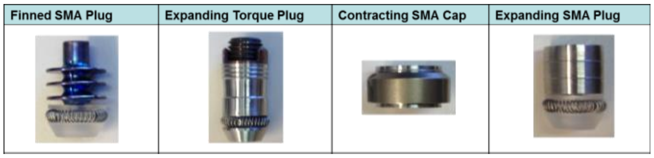
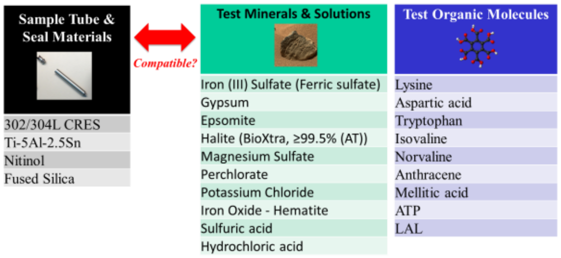


Figure 1. Phase II seal designs.

Seal Testing: Seal integrity is being assessed through measuring ultimate mechanical strength, burst pressure, and leak rate after subjected to thermal cycles, vibration, shock, abrasion, and dust. Each test was performed in triplicate using tubes which were dusted with Mojace Martian Simulant (MMS) (Figure 2) and an additional test using one clean tube for comparison. Results show that all three seals survive up to 1000 N of force before failure.

Thermal Cycle Testing: A custom built thermal chamber has the ability to perform He leak tests over temperature and pressure ranges of interest on dusty tubes filled with solid core samples. The chamber operates between -135°C and 80°C with a pressure from atmosphere down to 10^{-4} Torr. Initial helium leak test results for one of the contracting SMA ring cap test pieces reveal that at lower temperatures, the leak rate increases potentially due to relaxation of the SMA ring around the cap.

Material Compatibility: Materials used to construct the sample tube and seal were selected based on their compatibility with potential Martian sample minerals and organic molecules (Figure 3). Accelerated corrosion tests were performed on using coupons to determine the lifetime of the material of interest in the target environment. Furthermore, organic compatibility was assessed using the corresponding assay to determine if the target biomolecule was altered over the course of the accelerated corrosion test. Initial results show that ATP, LPS, and Lysene are not altered over time in Mars Regolith Simulant. Furthermore, we show that we are able to minimize organic contamination to a level below 3 ng/cm² in the case of pyrolized nitinol.



Sample Tube & Seal Materials
- 302/304L CRES
- Ti-5Al-2.5Sn
- Nitinol
- Fused Silica

Test Minerals & Solutions
- Iron (III) Sulfate (Ferric sulfate)
- Gypsum
- Epsomite
- Halite (BioXtra, ≥99.5% (AT))
- Magnesium Sulfate
- Perchlorate
- Potassium Chloride
- Iron Oxide - Hematite
- Sulfuric acid
- Hydrochloric acid

Test Organic Molecules
- Lysine
- Aspartic acid
- Tryptophan
- Isovaline
- Norvaline
- Anthracene
- Mellitic acid
- ATP
- LAL

Figure 3. Sample tube and seal materials, test minerals, and organic molecules used for testing.

The testing matrix used for these studies and its results will provide a useful infrastructure for future icy moon sample integrity tests.

References: [1] Mustard, J.F., et al., “Report of the Mars 2020 Science Definition Team,” Mars Exploration Program Analysis Group (MEPAG), Jul. 2013. [2] Younse, P., et al., “Sample Sealing Approaches for Mars Sample Return Caching,” 2012 IEEE Aerospace Conference, Big Sky, MT, Mar. 3-10, 2012.

BIG IMPACTS AND TRANSIENT OCEANS ON TITAN. K. J. Zahnle[1] D. G. Korycansky[2] and C. A. Nixon[3], [1]Space Science Division, NASA Ames Research Center, MS 245-3, Moffett Field CA 94035, United States of America (Kevin.J.Zahnle@NASA.gov), [2]CODEP, Department of Earth Sciences, University of California, Santa Cruz CA 95064, United States of America (dkorycan@ucsc.edu), [3]Planetary Systems Laboratory, Goddard Space Flight Center, Greenbelt MD 20771, United States of America (Conor.A.Nixon@NASA.gov).

Introduction: We have studied the thermal consequences of very big impacts on Titan [1]. Titan's thick atmosphere and volatile-rich surface cause it to respond to big impacts in a somewhat Earth-like manner. Here we construct a simple globally-averaged model that tracks the flow of energy through the environment in the weeks, years, and millenia after a big comet strikes Titan. The model Titan is endowed with 1.4 bars of N2 and 0.07 bars of CH4, methane lakes, a water ice crust, and enough methane underground to saturate the regolith to the surface.

We assume that half of the impact energy is immediately available to the atmosphere and surface while the other half is buried at the site of the crater and is unavailable on time scales of interest. The atmosphere and surface are treated as isothermal. We make the simplifying assumptions that the crust is everywhere as methane saturated as it was at the Huygens landing site, that the concentration of methane in the regolith is the same as it is at the surface, and that the crust is made of water ice. Heat flow into and out of the crust is approximated by step-functions. If the impact is great enough, ice melts. The meltwater oceans cool to the atmosphere conductively through an ice lid while at the base melting their way into the interior, driven down in part through Rayleigh-Taylor instabilities between the dense water and the warm ice. Topography, CO2, and hydrocarbons other than methane are ignored. Methane and ethane clathrate hydrates are discussed quantitatively but not fully incorporated into the model.

We find that a nominal Menrva impact would have been big enough to raise the surface temperature by ~80 K. Nominal Menrva would have doubled the methane inventory at the surface. The mobilized methane would have drizzled out of the atmosphere over hundreds of years, filling lake beds, oil pans, whatever. Uncertainties in the impact energy and the partitioning of the energy into the atmosphere correspond to a factor two uncertainty in the temperature rise. Menrva was probably not big enough to heat the 1.4 bar N2 atmosphere to the melting point of water, but some global-distributed surface melting cannot be ruled out at the high end of the uncertainty.

Bigger impacts are more invigorating. If Titan's surface is mostly made of water ice, the putative Hotei impact (a possible 800-1200 km diameter basin, [1]) raises the average surface temperature to 350-400 K. Global meltwaters might range between 50 m to more than a kilometer deep, depending on the size of the event and how rapidly bedrock ice warms and founders. Water rain must fall, flow, and pool, subject to choking and crusting over with flotsam, the later including a variety of hydrocarbons, some of them liquid. Global meltwater oceans do not last more than a few decades or centuries at most, but are interesting to consider given Titan's organic wealth. When it finally fully freezes the ocean would be on the order of a kilometer deep.

Hotei scale events, regardless of whether Hotei is itself a real exemplar, must have played a role in the history of Titan, as it is not plausible to build a world as big as Titan and not have big impacts.

Clathrate hydrates might form under some of the conditions discussed here. Unfavorable kinetics would seem to restrict formation of the binary methane hydrate to depths greater than ~1 kilometer of ice. Nonetheless it appears likely that methane migrating from below could have been caught in clathrates between 1 and 2 km depth, with capacity to store one to two orders of magnitude more methane than is currently in the atmosphere.

Impacts also create local crater lakes but, in disagreement with previous studies, we conclude that the lakes are likely to be deeply buried and very short-lived. The problem is that liquid water is denser than ice. Crater lakes form in shock-heated warm ice of relatively low viscosity. Rayleigh-Taylor instabilities in the warm ice grow quickly, the lakes founder, and the water mixes with ice. Any liquid water that remains unfrozen sinks to the bottom of the crater where it either pools kilometers below the surface in contact with cold bedrock ice. These concerns are general for any large icy satellite and not particular to Titan.

References:

[1] Zahnle K. J., Korycansky D. G., and Nixon D. G. (2013). *Icarus (in press).* [2] Soderblom L. A., Brown, R. H., Soderblom, J. M., Barnes, J. W., Kirk, R. L., Sotin, C., Jaumann, R., Mackinnon, D. J., Mackowski, D. W., Baines, K. H., Buratti, B. J., Clark, R. N., and Nicholson, P. D. (2009). *Icarus 204, 610–618.*