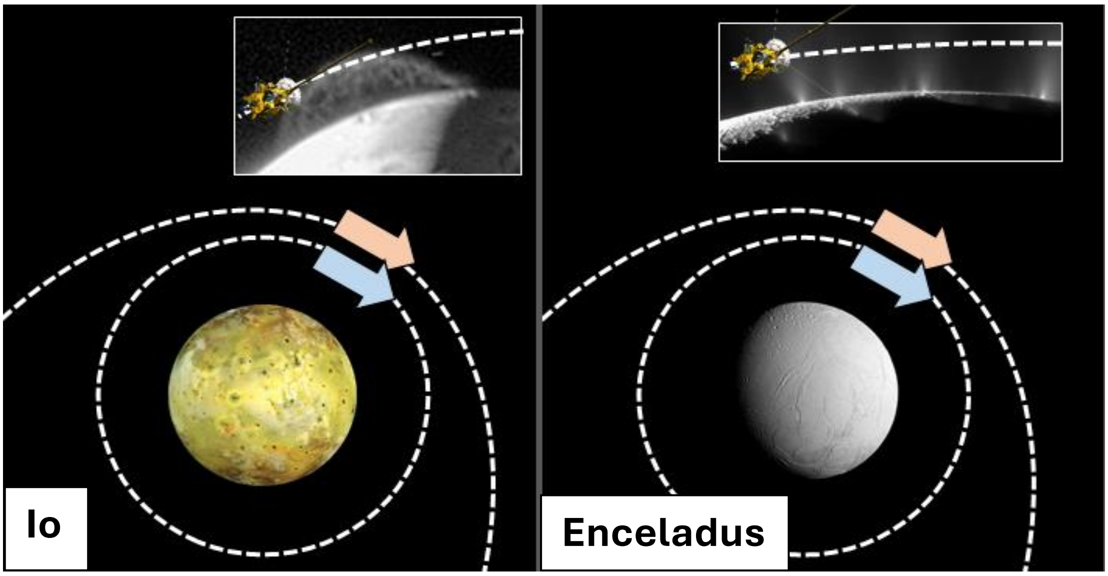
BLOWING HOT AND COLD:

EXPLORING THE PLUMES OF IO AND ENCELADUS

RAS G Meeting Dec 13th , Burlington House, Piccadilly (https://ras.ac.uk/events-and-meetings/ras-meetings/blowing-hot-and-cold-exploring-plumes-io-and-enceladus)



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The programme is on pages 2 and 3. This is then followed by the full abstract and author list of each talk and poster in the same order as the programme.

Programme:

10:25 Welcome, general introduction.

Morning Session: Enceladus

10:30 – 11:00 **Nozair Khawaja** (Univ. of Stuttgart and Freie-Univ. Berlin) – Invited talk: Enceladus as a Potential Oasis for Extraterrestrial Life.

11:00 – 11:15 **Jürgen Schmidt** (Freie-Univ. Berlin): The Enceladus Dust Plume from the Cassini Cosmic Dust Analyzer.

11:15 – 11:30 **Thomas R. O'Sullivan** (Freie-Univ. Berlin): On the dissociation behaviour of singly-substituted monocyclic aromatics in impact ionisation mass spectrometry and implications for the Enceladus subsurface.

11:30 – 11:45 **Anna Parsec-Wallis** (Mullard Space Science Laboratory, Univ. College London): Further analysis into the plumes of Enceladus.

11:45 – 12:00 **Mark G. Fox-Powell** (Open Univ.): Salt composition is a proxy for ice grain freezing rate in cryovolcanic plumes.

12:00 – 12:15 **Steve Armes** (Univ. of Sheffield): Synthesis of phenanthrene/pyrene hybrid microparticles: useful synthetic mimics for polycyclic aromatic hydrocarbon-based cosmic dust.

12:15 – 12:30 **Min Zeng** (Univ. of Sheffield): New Synthetic Mimic for Micrometer-sized Nitrogen-based Polycyclic Aromatic Hydrocarbon Cosmic Dust.

12:30 – 12:45 **Gillian Sclater** (Birbeck, Univ. of London): Modelling dissociating clathrates in the cryovolcanic vents of Enceladus.

12:45 – 13:00 Poster talks: **Angus Aldis** (Open Univ.), **Jessica Hogan** (Open Univ.), and **Duncan Lyster** (Oxford Univ.) will briefly introduce their posters (titles listed below) which will be on display during lunch.

Lunch

13:00 – 14:00 including display of posters.

Posters:

Angus Aldis (Open Univ.) Bubbles are rockets for microbes; predicting microbial dispersion in Enceladus's plumes based on bubbling in Iceland's geothermal springs.

Jessica Hogan (Open Univ.) Low-pressure freezing times of liquid droplets relevant to plume-forming regions on Enceladus.

Duncan G. Lyster (Oxford Univ.) Enceladus Thermal Mapper – A Multiband Radiometer for Global Mapping of Enceladus' Thermal Environment.

Afternoon Session: Io

14:00 – 14:30 **Ryan Ogliore** (The Washington Univ., St. Louis) – Invited talk: Io Plumes: Pyroclasts and How to Collect Them.

14:30 – 14:50 **Lionel Wilson** (Lancaster Univ.). Explosive volcanic eruptions on bodies with negligible atmospheres: Application to Io. (Online talk)

14:50 – 15:05 **Mark Burchell** (Univ. of Kent): Orbits at Io: Types, encounter speeds and peak shock pressures.

15:05– 15:25 **Xiaodong Liu** (Shenzhen Campus of Sun Yat-sen University, China): The quantity and distribution of stream particles deposited on Jupiter's icy moons. (Online talk)

15:25 – 15:30 Concluding Remarks

Enceladus as a Potential Oasis for Extraterrestrial Life (INVITED TALK)

Nozair Khawaja*[1,2], Frank Postberg[2], Ralf Srama[1]

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In 2004, NASA's Cassini-Huygens spacecraft arrived at Saturn and soon provided the first direct evidence for a plume of gas and ice grains emitted from surface fractures at the moon's south pole [1,2]. Enceladus was the first and currently only planetary body beyond Earth whose subsurface ocean material was sampled and analysed by spaceborne mass spectrometers onboard Cassini. The vented material from Enceladus contains both organic and inorganic chemical species. Further understanding of Enceladus plume material could provide insights into an abiotic or potentially biotic origin of such chemistry, constraining the presence or lack of extant subsurface life. A range of evidence supports the presence of a subsurface global saline ocean [3], which interacts with the moon's porous rocky core [4], where hydrothermal activity [5] and exothermic serpentinisation [6] reactions are ongoing. Enceladus ejects oxygen- and nitrogen-bearing volatiles and simple hydrocarbons in both the gas phase and in ice grains [7,8], alongside complex O- and N-bearing macromolecular organics in ice grains [9]. Other studies have also revealed the presence of phosphorus [10] and HCN [7] in the subsurface ocean. Recently, Khawaja et al. [11,12] reported the detection of ether/ethyl and ester/alkene group moieties in freshly ejected ice grains.

Compounds thus far detected at Enceladus are comprised of five (CHNOP) of the six (+S) biologically essential elements. These bioessential elements also contribute to hydrothermal chemistry and the synthesis of biologically relevant compounds, carrying significant implications for the habitability of the Enceladus ocean and therefore the search for life in the solar system. The nomination of Enceladus as the top candidate for ESA's next flagship mission has further enhanced the importance of investigating the chemical evolution of organics under Enceladean conditions. In this talk, we review the current state of knowledge about the composition of plume material and implications for planning the next Enceladus mission.

References: [1] Porco et al., 2006, Science, 311(5766), 1393-401 [2] Dougherty et al. 2006, Science, 311(5766), 1406-09 [3] Postberg et al., 2009, Nature, 459(7250), 1098-101 [4] Iess et al., 2014, Science, 519(6179), 78-80 [5] Hsu et al., 2015, Nature, 519(7542), 207-10 [6] Waite et al., 2017, Science 356(6334), 155-9 [7] Peter et al., 2024, Nature Astronomy, 8(2), 1-10 [8] Khawaja et al., 2019, MNRAS, 489(4), 5231-43 [9] Postberg et al., 2018, Nature, 558(7711), 564-8 [10] Postberg et al. 2023, Nature, 618(7965), 489-93 [11] Khawaja et al. EPSC2024-1055 [12] Khawaja et al., (in review)

The Enceladus Dust Plume from the Cassini Cosmic Dust Analyzer

Jürgen Schmidt[1],Frank Postberg[1], Lenz Nölle[1], Nozair Khawaja[1], Anastasiia Ershova[2] , Ralf Srama[3], Sascha Kempf[4], Ben Southworth[5].

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We analyse data recorded by the Cosmic Dust Analyzer (CDA) on board the Cassini spacecraft that were obtained during traversals of the Enceladus dust plume. The focus of our work are profiles of relative abundances of grains of different compositional types derived from mass spectra recorded with the Dust Analyzer (DA) subsystem during the Cassini flybys E5 and E17. The profile from E5, corresponding to a steep and fast (17.7 km/s) traversal of the plume, was analyzed in previous work (Postberg et al, 2011). Here we present and include into the analysis a second compositional profile obtained at a very different geometry during flyby E17, with a nearly horizontal traversal of the South Polar Terrain (SPT) at a significantly lower relative velocity (7.5 km/s). Additionally, we employ in our analysis rates of dust detections registered in the plume by the High Rate Detector (HRD) subsystem of CDA at two different Enceladus flybys (E7 and E21). We derive the ranges of grain sizes that were sampled by the two CDA subsystems at these flybys and use the data sets to constrain the parameters of a new dust plume model. That model we construct from a recently developed mathematical description of dust ejection (Ershova and Schmidt, 2021) using the software package DUDI, publicly available at https://github.com/Veyza/dudi. Further constraints we use for our model are published velocities of gas ejection and the positions of gas and dust jets on the SPT. From our model we derive production rates of dust mass for the different compositional types of grains detected by CDA, amounting to a total rate equal to or larger than about 28 kg/s. The contribution of salt-rich dust to the plume was previously believed to be dominant in mass, based on the analysis of E5 flyby data alone (Postberg et al, 2011). However, including both compositional profiles (E5 and E17) in our analysis, we find that the salt-rich dust contribution is only about one percent by mass or less. This finding follows in part from an improved understanding of the masses of grains of various compositional types that implies a generally smaller size for salt rich grains than previously thought. Furthermore, the E17 compositional profile exhibits a dominance of organic enriched grains over the SPT, a region of the plume that was poorly constrained, if at all, by the E5 data. Our new dust plume model can be used to predict numbers and masses for grains of various compositional types that a detector on a future mission will collect during a plume traversal.

The ice-volcanic activity of the icy Saturnian moon Enceladus (diameter 500 km) was one of the biggest scientific discoveries of the NASA/ESA mission Cassini-Huygens. Water vapor and small ice particles are emitted from an anomalously warm region around the south pole of the moon. This activity indicates the presence of liquid water beneath the ice shield of Enceladus and scientists are currently investigating the habitability of this subsurface ocean. With the data of the Cosmic Dust Analyzer on board the Cassini spacecraft, we have directly measured the composition of the ice particles from Enceladus, providing important implications for the composition of the ocean, too. A new space mission is planned by the European Space Agency to further investigate the Enceladus and its habitability. Our work provides important information for the preparation of such a mission.

On the dissociation behaviour of singly-substituted monocyclic aromatics in impact ionisation mass spectrometry and implications for the Enceladus subsurface

Thomas R. O'Sullivan[1], Nozair Khawaja[1,2], Lucía Hortal Sánchez[1], Maryse Napoleoni[1], Jon Hillier[1], Partha P. Bera[3,4], Frank Postberg[1]

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Cassini's observations at Enceladus revealed the presence of a diverse organic inventory [1,2] in its subsurface ocean as well as ongoing hydrothermal activity at the water-rock interface [3,4]. Ice grains and gases ejected into the plume contain compounds originating from the depths of the ocean, which are likely linked to hydrothermal (bio)geochemistry [1,2,5]. Understanding processes that may influence the detection of organic compounds in ice grains from Enceladus is crucial for evaluating its prospects for habitability and understanding how organics manifest in spacecraft mass spectra. Analogue spectra, generated in the laboratory using the laser-induced liquid beam ion desorption (LILBID) technique [6], are a vital tool for interpreting impact ionisation mass spectra, as produced by Cassini's Cosmic Dust Analyzer (CDA). Khawaja et al. [7] recently investigated the hydrothermal evolution of the simple peptide triglycine (GGG) and its detectability with impact ionisation mass spectrometry. Significant differences between the spectra of processed and unprocessed GGG were observed in this work, outlining an approach to verify a unique spectral fingerprint as evidence for hydrothermal activity.

In this talk, we discuss the role of computational chemistry simulations as an emerging technique for the analysis of impact ionisation mass spectra of ice grains. A range of aromatic compounds were detected in ice grains from Enceladus by CDA, both in Saturn's E ring and directly from the fresh plume [1,2,8]. Aromatics form part of larger macromolecular material with unfused rings, and may also be present as low mass organics in ice grains [1]. Hydrothermal activity at the seafloor of Enceladus may alter the substituent groups bonded to aromatic rings, favouring the formation of more stable compounds whilst keeping the aromatic ring intact [9].

It is evident that aromatic compounds do not simply dissociate at their weakest bonds in impact ionisation mass spectrometry, nor do they necessarily follow the lowest energy dissociation channels. Singly-substituted aromatics also produce similar mass spectral features regardless of the attached functional group. The water/ice matrix most likely plays a pivotal role in the fragmentation of organic compounds, influencing protonation site and thus the available dissociation channels. We discuss the relationship between aromatic molecules and hydrothermal activity, as well as the fragmentation behaviour of the aromatic ring in impact ionisation mass spectrometry.

References : [1] Postberg, F. et al. (2018) *Nature* **558**, 564–568. [2] Khawaja, N. et al. (2019) *MNRAS* **489**, 5231–5243. [3] Postberg, F. et al. (2011) *Nature* **474**, 620–622. [4] Hsu, H.-W. et al. (2015) *Nature* **519**, 207–210. [5] Waite, J. H. et al. (2017) *Science* **356**, 155–159. [6] Klenner, F. et al. (2019) *Rapid Commun. Mass Spectrom.* **33**, 1751–1760. [7] Khawaja, N. et al. (2024) *Phil. Trans. R. Soc. A.* **382**, 20230201. [8] Khawaja, N. et al. (2024). *Europlanet Science Congress,* EPSC2024-1055. [9] McCollom, T. M., et al. (2001) *Geochimica et Cosmochimica Acta* **65**, 455–468.

Further analysis into the plumes of Enceladus

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One of the unexpected measurements of the Cassini-Huygens mission was the discovery of heavy negative ions in the plumes of Enceladus and in Titan's upper atmosphere. Negative ions appear to be a feature of icy moons with subsurface oceans like Enceladus, signalling the potential for prebiotic chemistry. In this talk we will present the current analysis of Enceladus flyby E3 and the composition of this icy moon's plumes that can be resolved. Apart from current data analysis of the plumes at Enceladus, we will present the initial ideas of an instrument design for detection and analysis of negative ions ahead of the announced large-class ESA mission with mission targets being Enceladus and Titan.

Salt composition is a proxy for ice grain freezing rate in cryovolcanic plumes

Rachael E. Hamp[1] , Christoph G. Salzmann[2] , Peter Fawdon[3] , Zachary Amato[3,4], Milz L. Beaumont[2] , Hannah E. Chinnery[3] , Thomas F. Headen[4] , Paul F. Henry[4] , Liam Perera[5] , Stephen P. Thompson[5] and **Mark G. Fox-Powell***[1]

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Populations of salt-rich ice grains within the plumes of Enceladus are believed to originate as droplets of ocean water and have provided valuable information on the chemistry and habitability of the ocean below. Analysis of ice grains by Cassini have implied an alkaline ocean with a composition dominated by sodium, chloride and carbonate. However, little is currently known about how the composition of these droplets evolve as they are subjected to the extreme changes of temperature and pressure within the plume environment. We studied how the solid phase composition of sodium chloride (NaCl) ices varies as a function of cooling rate. Our work has revealed the presence of a previously unrecognised NaCl dihydrate formed upon freezing of solutions at cooling rates relevant to plume activity at Enceladus. This new hydrate expands on the recently identified NaCl hydrates formed in high-pressure experiments [1], and together with these reveals a rich phase behaviour in the low temperature Na-Cl-H2O system that had been overlooked for over 150 years. Using neutron and X-ray diffraction, we show that the new material is structurally related to, although distinct from, hydrohalite, the only other known dihydrate of sodium chloride, and converts to hydrohalite upon warming above ~190 K.

Our findings indicate that the NaCl phase present in plume ice grains could act as a proxy for cooling rate, helping to constrain the thermal history of plume material. Cooling rates below 80 K min-1 were found to form only hydrohalite, while cooling rates exceeding 130 K min-1 formed only the new material. Between these rates, a mixture of crystalline NaCl phases were observed. At the fastest rates produced by ‘quench' cooling (>~600 K min-1), only noncrystalline amorphous salt was observed. Finally, we show that the new hydrate possesses near-infrared and Raman spectral features that are distinct from hydrohalite, and thus could be used to identify it with existing or future observations at Enceladus. Additionally, the presence of the new hydrate could indicate regions where salty fluids have rapidly cooled at other icy worlds with potential plumes, such as Europa.

References:

[1] Journaux et al., (2023); PNAS, 120 (9) e2217125120

Synthesis of phenanthrene/pyrene hybrid microparticles: useful synthetic mimics for polycyclic aromatic hydrocarbon-based cosmic dust

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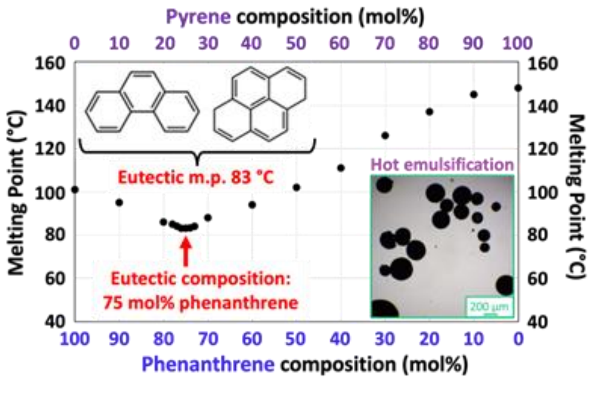
Abstract. Polycyclic aromatic hydrocarbons (PAHs) are widely regarded to be a major source of carbon, which has implications in the ongoing search for complex organics on Enceladus and other icy ocean moons in our solar system. Herein we report the first synthetic mimics for PAH-based cosmic dust. First, we construct a melting point phase diagram (see below) for a series of phenanthrene/pyrene binary mixtures to identify the eutectic composition (75 mol% phenanthrene) and its melting point (83°C). The molten oil obtained on heating this eutectic composition to 90°C in aqueous solution is homogenized in the presence of a water-soluble polymeric emulsifier. On cooling to 20°C, polydisperse spherical phenanthrene/pyrene hybrid microparticles are obtained. Varying the stirring rate and emulsifier type enables the mean microparticle diameter to be adjusted over a wide range (from 11 to 279 μm). Importantly, the phenanthrene content of *individual* microparticles remains constant during processing, as expected for the eutectic composition. These new hybrid microparticles form impact craters and undergo partial fragmentation when fired into a metal target at 1 km s^{-1} using a light gas gun. When fired into an aerogel target at the same speed, microparticles are located at the ends of characteristic 'carrot tracks'. Autofluorescence is observed in both types of experiments, which at first sight suggests minimal degradation. However, Raman microscopy analysis of the aerogel-captured microparticles indicate prominent pyrene signals but no trace of the low m.p. phenanthrene component. Such differential ablation during aerogel capture is expected to inform the *in situ* analysis of PAH-rich cosmic dust in future space missions.

A full description of this work is at: https://pubs.acs.org/doi/full/10.1021/jacs.4c04330



New Synthetic Mimic for Micrometer-sized Nitrogen-based Polycyclic Aromatic Hydrocarbon Cosmic Dust

Min Zeng[1] and Steven P. Armes[1]

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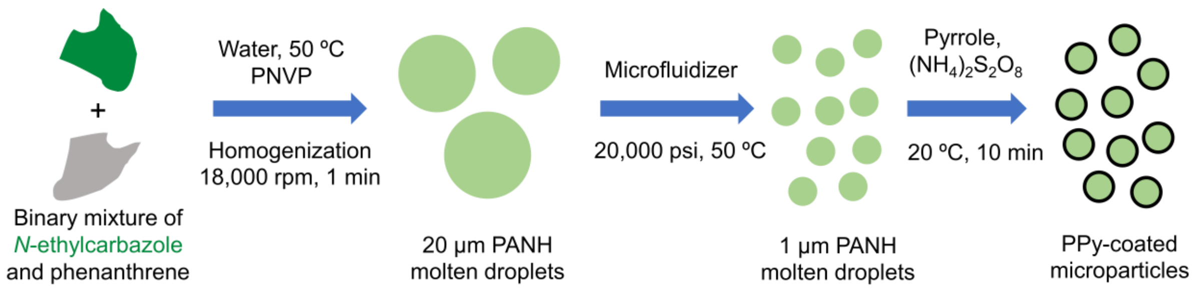
Abstract. Polycyclic aromatic hydrocarbons (PAHs) are known to be an abundant extraterrestrial source of carbon. Moreover, nitrogen-based PAHs (a.k.a PANHs) provide a plausible link to prebiotic nucleobases that have been detected in meteorites. Herein we report the preparation of the first synthetic mimic for nitrogen-based PAH-based cosmic dust. A melting point (m.p.) phase diagram is constructed for a series of binary mixtures of *N*-ethylcarbazole (m.p. = 71 °C) and phenanthrene (m.p. = 99 °C) to identify the eutectic composition, which corresponds to 60 mol% *N*-ethylcarbazole (m.p. = 43 °C). This eutectic composition is then processed via hot emulsification using a water-soluble polymeric emulsifier [poly(*N*-vinylpyrrolidone), PNVP]: high-shear homogenization at 50 °C produces molten oil droplets of approximately 20 μm diameter. This precursor emulsion is then subjected to high-pressure microfluidization using a commercial microfluidizer at 50 °C to produce much finer molten oil droplets of approximately 1 μm diameter. On cooling, these molten oil droplets crystallize to form microparticles, which can be subsequently coated with an ultrathin overlayer of polypyrrole (PPy) using a well-known aqueous deposition protocol. This electrically conductive coating should enable efficient accumulation of surface charge within a 3 MV Van de Graaff accelerator and hence allow electrostatic acceleration of such microparticles up to the hypervelocity regime that typifies the behavior of fast-moving cosmic dust.

Figure 1. Schematic representation of the synthesis of polypyrrole-coated PANH-based microparticles.



Modelling dissociating clathrates in the cryovolcanic vents of Enceladus.

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Clathrates are thought to be abundant in the outer solar system, where they are likely to be an important constituent in the interiors of icy satellites. During planetary accretion, clathrates may have trapped large quantities of gas directly into protoplanetary condensates and methane clathrate is thought to have been the predominant methane containing phase in the nebula from which Saturn, Uranus, Neptune and their moons formed. It has been suggested that the abundance of gases observed in the plumes erupting from the fractures on the south polar region of Enceladus are the result of the dissociation of clathrate hydrates.

Clathrates are crystalline inclusion compounds of hydrogen-bonded water molecules that trap non-polar guest molecules (e.g., CH_4, CO_2 and N_2) and are thermodynamically stable at high pressures and low temperatures. Under conditions which destabilize their equilibrium structure, clathrate hydrates dissociate, breaking the host water lattice, releasing the encaged gas molecules. The dissociated or exsolved gas released into a cryomagma can drive explosive eruption and ice fountaining, comparable to terrestrial basaltic fire fountains caused by volatile exsolution.

It is plausible that the decompression dissociation of clathrate hydrates entrained in xenoliths provides a mechanism for driving the explosive cryovolcanism in the south pole of Enceladus and the numerical model presented here has been developed to represent the physical, chemical and thermodynamic processes considered likely to prevail on Enceladus. The xenolith model quantifies the fragmentation depths, flow dynamics, kinetic energy and viscosity of the plumes. Selected conduit sizes are related to the plume heights, velocity and flow rates, and several different cryomagma composition scenarios (liquid and volatile content) are examined, providing a range of outcomes which are compared to the observational data from Cassini. The model also estimates the thermodynamic energy balance of the plumes to account for the contribution made by clathrate dissociation to the energy radiated by the plumes (latent heats of dissociation, crystallization and sublimation).

Bubbles are rockets for microbes; predicting microbial dispersion in Enceladus's plumes based on bubbling in Iceland's geothermal springs. (POSTER)

Angus Aldis[1*], Mark Fox-Powell[1], Karen Olsson-Francis[1], Ben Stephens[1], Toni Gladding[2], Tim Goodall[3].

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The Cassini mission confirmed Enceladus has a sub-surface ocean that is hydrothermally active and contains the ingredients for life. The moon also produces supersonic plumes that eject aerosolised droplets of ocean water into space, likely formed by vigorous bubbling of hydrothermal gases. Dependent on these bubbling mechanics, if life is present in the ocean, long distance microbial dispersion may occur via the plumes allowing for sample collection by spacecraft. Despite this theory, it is unknown how, or what, evidence of microbial life might be transferred into the plumes. Here results from a field campaign that used Iceland's geothermal springs as analogue sites for Enceladus plume formation are discussed. Iceland was selected as its geothermal springs and Enceladus's ocean share aerosolization driven by bubbling of hydrothermal gases and both host niches for chemotrophic microbial communities. In situ sampling and aerosol monitoring was undertaken at Ölkelduháls, within the Hengill volcanic massif, next to bubbling hot springs, and in the background environment. Aerosol monitoring data indicate these springs produce and eject orders of magnitude more particulates compared to the background environment. It was observed that the abundance of spring aerosol also sharply decreased with distance, with particulate abundance returning to background levels at ~17 metres from the springs. Planned Flow Cytometry, 16S rRNA sequencing, Spectroscopy and Spectrometry will determine the chemical composition of the springs and whether they contain biological material. It will then be understood if spring chemical composition or potential microbial community are entirely or limitedly represented in ejected aerosol. By understanding the dispersal of potential microbes in aerosols, this work can help future space mission planners decide at what fly by altitude in the plume may have the highest chances of detecting evidence of life.

Low-pressure freezing times of liquid droplets relevant to plume-forming regions on Enceladus (POSTER)

Jessica Hogan[1], Mark Fox-Powell[1],Rachael Hamp[1], Jonathan Merrison[2], Jens Jacob Iversen[2], Victoria Pearson[1], Manish Patel[1]

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The plumes of Saturn's moon Enceladus emit water vapour and ice grains from cracks in the ice shell, fed by conduits/vents that transport subsurface ocean material to the surface. Cassini mission data revealed there is variation in the composition of ice grains entrained within the plumes. Salt-rich "Type III" ice grains are interpreted to originate as dispersed ocean spray droplets representative of source liquid reservoir composition. Type III grains can therefore be used as a tool to interpret the chemistry and habitability of the otherwise inaccessible subsurface. However, the effects of rapid temperature and pressure changes on the freezing rates of ice grains during eruption remain unknown, which are vital in determining how ocean salts are transferred into observed plume particles. Freezing rate is a determining factor for ultimate ice grain composition, as salt segregation during the freezing process can cause dramatic variations in salt concentrations between grains, thus it is a vital parameter to quantify.

We have investigated the freezing times of salty liquid droplets analogous to droplets within the vents at Enceladus, under conditions predicted to occur at the liquid ocean to vapour interface (≤ 6 mBar). We employed the Aarhus Wind Tunnel Simulator II at Aarhus University to inject pure water and NaCl droplets into low-pressure (0.2 – 6 mBar) environments. The effect of pressure and salinity on freezing time was analysed using high-speed videography and laser doppler velocimetry. In addition, we observed droplet behaviour during the freezing process to explore the potential for fragmentation that could link to variation in salt-rich grain compositions.

We will present estimates of freezing time as a function of pressure relevant to droplets in plume-forming conditions. Secondary to this, through assessing ice grain impacts, we have quantified the proportions of grains that tend to fragment after evaporatively cooling and freezing at low pressures.

Future work will build on this to explore the composition of ice grains produced through evaporative cooling under predicted vent conditions. Our findings are therefore crucial in understanding plume material formation processes at Enceladus and other cryovolcanically active bodies, such as Europa.

Enceladus Thermal Mapper – A Multiband Radiometer for Global Mapping of Enceladus' Thermal Environment (POSTER)

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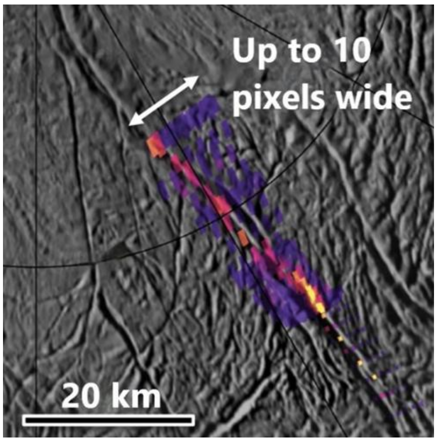
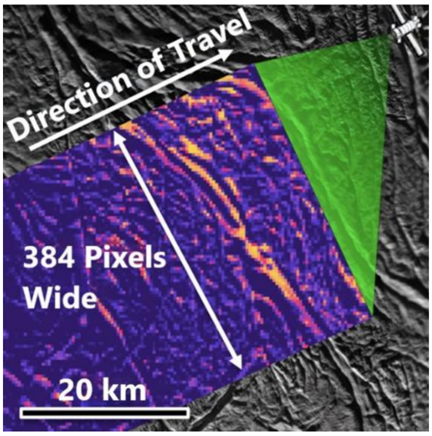
We present the results of an initial study into the feasibility and design of the Enceladus Thermal Mapper (ETM) instrument, designed to provide detailed temperature data for Enceladus, an icy moon of Saturn identified by the Cassini Mission as a prime candidate for astrobiological study due to its subsurface ocean and active cryovolcanism. Building on heritage from previous missions including TechDemoSat-1, Mars Climate Sounder, and Lunar Trailblazer, ETM aims to measure temperature variations across Enceladus' surface, including at the poles during the extreme cold of winter, when they can reach as low as 45 K [1]. Where Cassini provided limited high-resolution flyby data of Enceladus due to its Saturn-centric orbit, ETM, in orbit around the icy moon will offer continuous high-resolution thermal mapping with a 384 x 288-pixel sensor, capable of 80 m/pixel resolution from the 150 km altitude anticipated in preliminary mission concepts. This high heritage instrument will measure Enceladus' day, night, and polar-night temperatures, characterising the moon's activity, and surface properties. This will improve constraints on the Enceladus' global conductive heat loss, and better characterise and contextualise its active South Polar Terrain. The extreme cold of the Saturn environment necessitates adaptations in the previously lunar-focused filter assembly. To optimise the instrument's filters for thermal emission measurements, a digital model of the filter assembly was developed. This lightweight, low-power instrument is capable of significantly advancing the understanding of Enceladus' geological behaviour and evaluating its potential habitability by providing comprehensive temperature data essential for interpreting its evolution.

We will discuss the newly developed multispectral thermal instrument filter assembly model, which creates a framework for systematically optimising bandpass filter selection to meet scientific goals. Optimal filter choices will enable the determination of the full seasonal and diurnal range of Enceladus' thermal emission, allowing for precise temperature measurements with a goal of improving constraints on global thermal emission due to tidal heating. The suitability of different filter assemblies for different science goals will be discussed.



Cassini Thermal Map
[NASA/JPL/GSFC/SWRI/SSI (2010)]



ETM Thermal Map: (Visualization)

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Io Plumes: Pyroclasts and How to Collect Them (INVITED TALK)

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Volcanic plumes on Jupiter's moon Io erupt material hundreds of kilometers into space, offering the opportunity to collect and return a sample of Io to Earth for laboratory study. A mission concept for Io sample return is being developed for NASA's New Frontiers program. A detailed understanding of pyroclast formation, entrainment in the plume, hypervelocity collection by the spacecraft, and laboratory analysis of the Io sample are all critical for the success of an Io sample return mission.

Volcanically-emplaced sulfur and sufur dioxide are seen in abundance on Io's surface. Progressive burial by later eruptions carries deposits to depths where they melt to form thiofers. Magma rising through dikes from deeper mantle levels can entrain these volatiles. Io's plumes are likely driven by the explosive eruption of magma in a vent as the sulfur-dominated volatiles exsolve from the magma and expand. The sizes and total amount of pyroclasts in an Io plume can be estimated from the bubble sizes of the exsolving and expanding sulfur, and the radii of the sulfur dioxide and silicate ring deposits on Io's surface surrounding the plumes. We will present a model of magma fragmentation and pyroclast size in Io's Prometheus plume.

Bulk isotope measurements of collected Io pyroclasts would have an enormous impact on cosmochemistry, as our currently available samples are limited to the Sun, the terrestrial planets/satellites, the asteroid belt, and sub-milligram quantities of material from comets. It is possible to measure isotopes of hydrogen through osmium in hundreds of milligrams of pyroclasts collected from Io at hypervelocity, but it is important to choose the right collector material for each element. We have conducted light gas gun experiments at the University of Kent to simulate the collection of Io pyroclasts (using ground Hawaiian glass as an analog) into different possible materials (e.g., gold, indium, germanium, and silicon). We will present initial results from laboratory analyses of these analog shot experiments.

Explosive volcanic eruptions on bodies with negligible atmospheres:

Application to Io.

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Io demonstrates probably the most extreme examples of explosive volcanic activity that the Solar System has ever seen, but its eruptions must obey the same physical laws as those on other atmosphere-less bodies like the Moon, Mercury, and some differentiated asteroids in the distant past and, indeed, the Earth today. The differences are in the environmental controls. If an atmosphere is present, the exsolution of dissolved volatiles is rapidly diminished, and the expansion of the released volatiles ceases, as magmas reach the surface. This limits the extent of fragmentation of the magma into pyroclasts. In a vacuum, all nucleated gas bubbles attempt to expand indefinitely. The extreme demonstration of this is provided by the sub-millimetre pyroclastic glass droplets, returned by the Apollo missions, which are the main products of explosive eruptions on the ancient Moon. Similar processes must occur on Io. Furthermore, acceleration of entrained pyroclasts as released gases expand is also truncated by the presence of an atmosphere. In a vacuum, expanding gas accelerates particles until the pressure is so low that the mean free path of the molecules is larger than the typical particle sizes, and interactions effectively cease. I shall discuss how these issues relate to our ability to predict pyroclast sizes in eruptions on Io.

Orbits at Io: Types, encounter speeds and peak shock pressures

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We discuss the types of orbits one could use to study the plumes of Io. These consist of orbits of the satellite itself (we consider as examples circular and elliptical), orbits of Jupiter which include fly-bys of Io, and heliocentric orbits featuring a fly-by of Jupiter and which involve passing close to Io. Based on these, we predict encounter speeds at Io as a function of altitude, and then calculate the associated peak impact induced shock pressures for a range of collector materials. A similar analysis was recently carried out for Saturnian satellites (Burchell and Wozniakiewicz, 2004) , and so the results for Io are contrasted with those for Enceladus.

References:

Burchell, M.J. and Wozniakiewicz, P.J. Icy Ocean Worlds, Plumes and Tasting the Water. *Meteoritics and Planetary Science* **59**(6), 1358 – 1406, 2024. **https://doi.org/10.1111/maps.14152**

The quantity and distribution of stream particles deposited on Jupiter's icy moons.

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1. Introduction.

The phenomenon of Jovian dust streams is one of the major discoveries of the Ulysses [1]. Subsequently, the Galileo and Cassini also detected these extremely fast and tiny dust particles [2][3]. These nano-sized dust particles acquire a positive potential in Jovian plasma environment through various charging mechanisms and then rapidly escape the magnetosphere under the influence of Jupiter's co-rotating electric field. For more details concerning the Jovian dust streams, the reader may refer to the reviews of Krüger et al. [4] and Hsu et al. [5]. During the escape process, some stream particles (mainly composed of NaCl [3]) may be transported to the surface of the Jupiter’s icy moons (Europa, Ganymede, and Callisto), providing an exogenic source of salts to these icy moons. Investigating the quantity and distribution of stream particles deposited on Jupiter's icy moons could help the Europa Clipper and JUICE missions to better assess the composition of endogenous salts in the ice shell, and thus provide a glimpse into the material composition of the subsurface oceans. In addition, it could help researchers analyze the dielectric properties of salty ice, assess the radar signal penetration and attenuation in salty ice, and thus more accurately interpret radar echo signals from subsurface ice structures.

2. Methods and Results

By performing orbit integrations of many charged dust particles originating from Io, we investigate the quantity and deposition characteristics of streams particle delivered to the surfaces of the Jupiter's icy moons. Here, we report on our results. The mass accretion rates of Jovian dust streams on Europa, Ganymede, and Callisto are approximately 210 kg year−1 , 155 kg year−1 and 33 kg year−1 , respectively. Overall, stream particles preferentially implant into the trailing sub-Jovian quadrant of Jupiter’s icy moons. However, the specific deposition characteristics of stream particles on different icy moons differ significantly. Stream particles can deposit on the entire surface of Europa, but not on the leading anti-Jovian quadrant of Ganymede and Callisto. Only smaller stream particles can deposit on the leading anti-Jovian quadrant of Europa. These can be explained by the trajectory characteristics of stream particles with different radii. (Continues on next page).

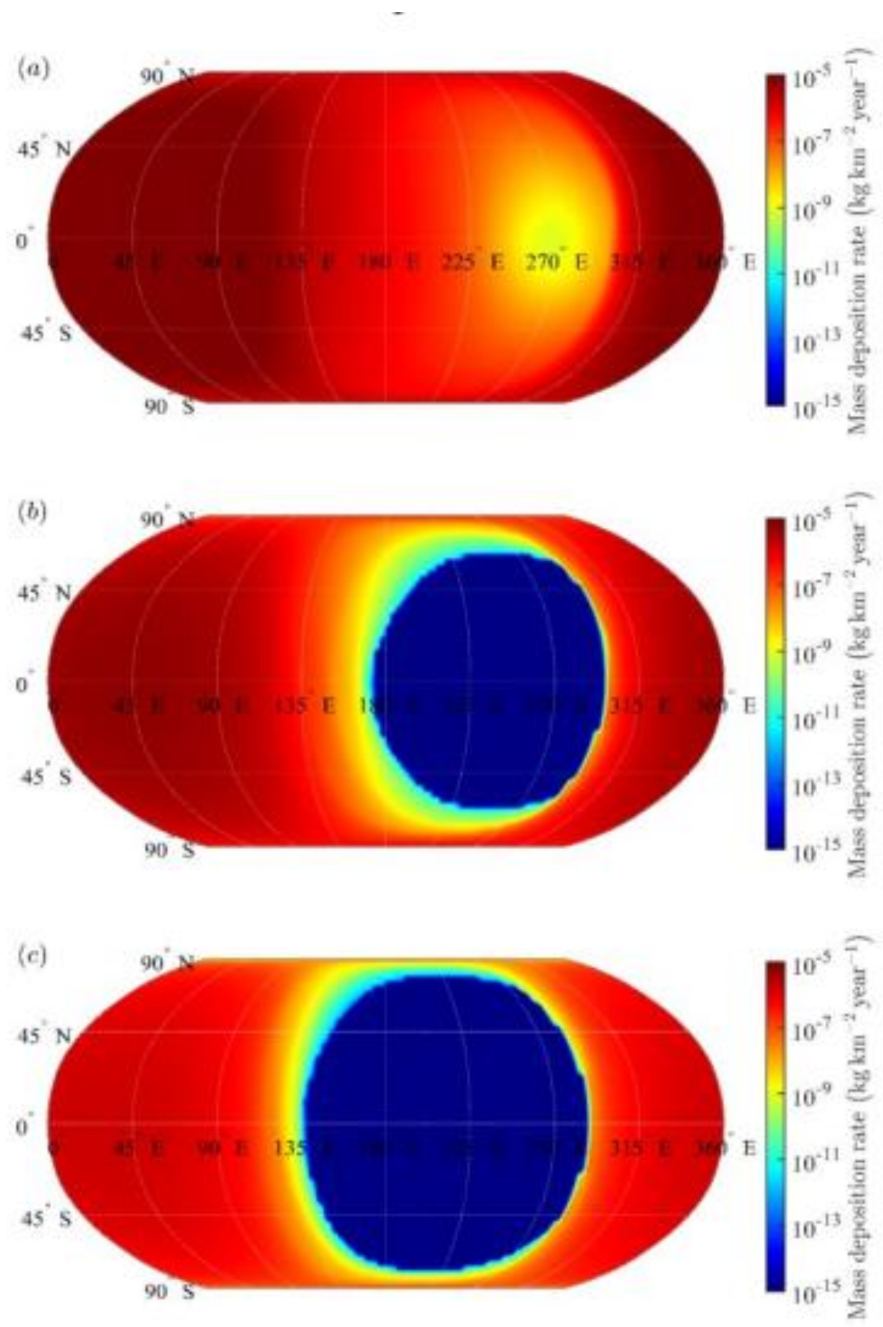

Fig.1 Mass deposition rate on the surface of (a) Europa, (b) Ganymede and (c) Callisto, respectively. The surface of each moon is divided into four quadrants according to the longitude range: trailing sub-Jovian (0°–90°E), trailing antiJovian (90°E–180°E), leading anti-Jovian (180°E–270°E), and leading sub-Jovian (270°E–360°E).

3. References.

[1] E. Grün et al. (1993) *Nature*, **362**:428–430. [2] E. Grün et al. (1996) *Nature*, **381**:395-398. [3] F. Postberg et al. (2006) *Icarus*, **183**:122-134. [4] H. Krüger et al. (2007) in: “Jupiter: The Planet, Satellites and Magnetosphere”, 219-240, pub. CUP, ISBN 9780521035453. [5] H.W. Hsu et al. (2012) in: “Nanodust in the solar system: discoveries and interpretations”, 77–117, pub. Springer, ASSL vol. 385.

Notes