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Salt-Ice Grain Formation in the Enceladus Plume: A Combined Experimental and Remote Sensing Approach

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Introduction: Enceladus is a moon of Saturn situated in the outer Solar System and is characterised by an icy crust and notable plumes of water vapour emerging from a subsurface liquid reservoir at its south pole [1]. Such plumes are our most compelling example of cryovolcanism in the Solar System, offering an accessible window into the subsurface ocean, which may host conditions favourable to the emergence of life [2].

Material ejected from the plumes have been identified as water vapour and microscopic ice grains, containing salts and organics [3,4], by the Cassini spacecraft. Unlike salt-poor Type I and organic-rich Type II grains, believed to originate from vapour condensation within the vents - salt-rich Type III grains are interpreted to be rapidly frozen ocean spray, critical to the investigation of the subsurface ocean, as they best preserve ocean composition [4]. Type III ice grains present a unique opportunity to probe subsurface ocean composition, therefore understanding their formation and how plume processes might alter their composition and distribution is crucial. Furthermore, properties of Type III icy particulates can be used as a proxy to reflect the subsurface conditions that influenced their formation, such as ocean salinity and salt abundance – assuming salt-rich grains are frozen droplets directly from the subsurface liquid [4].

It is known that Enceladus has a differentiated structure, with a solid rocky core overlain by a global scale liquid, subsurface ocean and an outer icy shell [8]. It is likely that liquid filled cracks in the ice shell transport liquid matter from the ocean, through vents, and into space [2], feeding Saturn's E-ring or depositing on the surface. It is in these vents where droplets of ocean spray fluid experience rapidly changing conditions, including temperature and pressure variations, that result in the formation of the various types of ice grains prior to eruption.

Further to this, there have been observations of size-dependent, compositional stratification identified in the plume [5], wherein larger salt-rich grains fall back along the surface and smaller salt-poor grains are ejected further from the source jets. Consequently, inferences about the subsurface ocean based upon in situ observations of the plume may not provide an accurate reflection of the interior of Enceladus, because of the poorly constrained impact of stratification during the eruption process. It remains inconclusive how cryovolcanic conditions affect the formation of Type III ice grains: in terms of particle size, composition, and the subsequent trajectories of icy plume material upon eruption into the space environment where detected.

This work will combine laboratory experiments, paired with data modelling and remote sensing data analysis to investigate the formation and distribution of salty ice grains in cryovolcanic settings, relevant to that of Enceladus and other icy moons.

Methodology: Using a bottom-up approach, we will experimentally simulate ice grain formation, varying parameters such as grain size, and organic content to address the importance of each parameter in defining the composition of ice grains [5, 6]. Utilising analytical techniques such as X-ray diffraction, scanning electron microscopy and Raman spectroscopy, we will then probe the microstructure and composition of the grains. Collecting near-infrared spectra under cryogenic conditions will also enable compositional comparison between laboratory findings and Cassini's Visible and Infrared Mapping Spectrometer (VIMS) instrument data [7]. We aim to address plume stratification by quantifying compositional and spectral differences between the largest grains (deposited near the jet sources) and smaller grains (that have the potential to achieve escape velocity and end up in the E-ring), as well as how the presence of organics can influence forming ices.

Implications: Ultimately, combining experimental results with models that predict ejection distances of different grain sizes and compositions will enable us to make predictions about the compositional stratification of the plume. Using Cassini VIMS observations of the active south polar region, we intend to test these predictions by seeking evidence for plume fall out. This context will help build an understanding of plume dynamics and composition at Enceladus and other icy ocean worlds with possible plumes, such as Jupiter's moon Europa.

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